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Reconstructing Quaternary landscapes and hydrology from soil survey maps

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Reconstructing Quaternary landscapes and hydrology from soil survey maps

by

Bradley Allen Miller

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Co-majors: Soil Science and Water Resources

Program of Study Committee:
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C. Lee Burras, Co-major Professor
Andrew Manu
Robert Lowry

Iowa State University

Ames, Iowa

2006

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GENERAL INTRODUCTION

Soils provide a historical record of the conditions under which they were formed. The soil formation factors described by Jenny (1941) are an open ended list that includes climate, organisms, relief, parent material, and time. These factors are a method for identifying the mechanisms which cause a soil to have certain properties. They are also a method to identify the formation environment from properties observed today. Time continues to change soils, but the processes are usually slow enough that the effects of long term conditions can be observed decades after a condition is gone. Understanding these connections allow historical reconstructions of the landscape, hydrology, wildlife habitat, and potentially other areas of interest.

In the United States Department of Agriculture's mission to provide useful information for agricultural production, it has produced an extensive map that details the properties of soils. When the survey began in 1899, it used large delineations that produced only a generalized representation of the landscape. The survey has progressively increased the level of detail included in its mapping. The level of detail now included in the survey is such that practically every formation factor identified by Jenny can be seen in the survey map. However, the soil survey attributes have been primarily agriculturally focused and analyzed at the county level. Regional maps of soils have usually been large delineations of soil type generalizations. The recent implementation of the soil survey in a nation wide geographic information system (GIS) format allows regional scale management and interpretation of the spatial data associated with the soil survey.

Parent material is the starting point for all soils. Identifying the parent material by texture, mineralogy, etc. enables an assessment of the process that deposited it there. Soils' origins are therefore the product of the most recent geologic event. The fine line between geology and soil science almost entirely rests on the transition between deposition and everything that happens thereafter until the deposit is buried. Because resources for producing Quaternary geology maps are usually limited, existing Quaternary geology maps are often generalized regions of the majority Quaternary deposits. The soil survey is a field observed map of Quaternary deposits. With proper interpretation, it can be used to create a Quaternary geology map that has more detail than currently available Quaternary geology maps.

A dominant force in soil formation is water. It is the underlying driver of soil formation within relief and climate. Water is such an important influence on soil properties that it may justify being listed separately. Where water has saturated the soil, there are generally anaerobic conditions. Anaerobic conditions cause decomposition to be suppressed and minerals to be reduced. The suppressed decomposition can be observed in a soil as a thick dark horizon caused by accumulating organic matter. If there is sufficient ponding, an O-horizon forms. These accumulations of organic matter are generally included in soil taxonomy as histic epipedons (Soil Survey Staff, 2003). Reduced minerals can be observed by gleyed horizons and other redoximorphic features (Khan & Fenton, 1994; Vepraskas, 1994; Richards & Vepraskas; 2001). These soil properties can be used to answer questions about the historical behavior of water.

The prairie pothole region is recognized as an area of some 770,000 km^2 extending from Alberta to north central Iowa that is characterized by many depressional wetlands. Those wetlands have been associated with producing between 50% and 80% of North Americas waterfowl (Batt et al., 1989). The southern Des Moines Lobe is the landform created by Wisconsinan glaciation that comprises the southeastern part of the prairie pothole region. Historical documentation refers to the southern Des Moines Lobe area as an area of vast swamps (Beauchamp, 1987). This region has since been almost completely drained. The majority of that drainage happened around the 1900s, leaving behind little information about the extent of the wetlands before settlement.

Because the soil survey maps the location of soils with the properties typifying upland ponding conditions, the location of historical depressional wetlands can be deduced. Obtaining wetland area and then its watershed area enable the calculation of the watershed to wetland area ratio. The watershed to wetland area ratio can be used to predict water regimes in depressional wetlands (Galatowitsch and van der Valk, 1994). The water regime of a wetland is an important factor for vegetation structure and dynamics (van der Valk and Davis, 1978).

The glaciation that defines the Des Moines Lobe created a new landscape. Stream networks have since eroded headward from channels of glacial outwash, but they have only added part of the landscape to their contributing area. The area that is not surficially connected to the stream network is referred to as the non-contributing area. Digital techniques for identifying non-contributing areas have been difficult because the challenges of locating true surface hydrologic end points, especially in areas of low relief. A map of depressional wetlands created from the soil survey is also a map of the hydrologic end points in the non-contributing area. The total of their watersheds is an estimation of the non-contributing area.

Artificial drainage has caused a major shift in the hydrologic cycle of this region. Historically, water leaving the non-contributing area mostly went to the atmosphere. Installation of artificial drainage has shifted the path of water leaving the non-contributing area to the stream network. Delineating the area of this historically non-contributing area provides a way to estimate water quantity changes due to artificial drainage.

This study was done to investigate the pre-settlement condition of the southern Des Moines Lobe landscape, with particular interest in the hydrological function of depressional wetlands. Information about the shape and hydrology of the land was found in the soil survey. Surface flow paths were modeled using the best available digital elevation model. Results from this study will be used to provide general mapping of Quaternary geology, identification of historical depressional wetland extents, information about the hydrologic properties of these wetlands, an estimation of the regional non-contributing area, and the general impact that draining the non-contributing area has had on stream flow.

Thesis organization

This thesis contains three chapters, each consisting of a paper to be submitted to an appropriate journal. Chapter 1 will be submitted to Quaternary Geology, with the following authorship: Bradley A. Miller, C. Lee Burras, and William G. Crumpton. Chapter 2 will be submitted to Journal of Environmental Quality, with the following authorship: Bradley A. Miller and William G. Crumpton. Chapter 3 will be submitted to Water Resources Research, with the following authorship: Bradley A. Miller and William G. Crumpton.

In addition to the three included papers, this thesis contains General Introduction and General Conclusions sections. References cited in both sections follow Appendix B.

CHAPTER 1. USE OF SOIL SURVEY MAP UNITS TO DEVELOP A DETAILED QUATERNARY GEOLOGIC MAP OF THE DES MOINES LOBE IN IOWA AND MINNESOTA

A paper to be submitted to Quaternary Research

Bradley A. Miller, C. Lee Burras, William G. Crumpton

Abstract

Maps of Quaternary deposits are often either geologic or pedologic. Geologic maps tend to integrate large areas without a lot of spatial detail. Pedologic maps contain more detail, but are difficult to integrate across geologic regions. This study created a Quaternary geologic map by categorizing soil descriptions into a geologic context and joining the attributes with the Soil Survey Geographic (SSURGO) database in ArcGIS®. The resulting map communicates many of the spatial intricacies of the Des Moines Lobe landform with 19 map units based on parent material. The display of these map units show detailed features of ground moraine, stagnation moraine, glacial lakes, outwash, and loess deposits. Qualitative visual assesment shows that the categorized soil map has generally good agreement with existing Quaternary geologic maps.

Introduction

The development of soil science followed shortly after the development of geology in the early 19th century. Many of the early soil surveyors were geologists who conceived soils as mainly the weathering products of geologic formations. Eugene W. Hilgard, as the Assistant State Geologist of Mississippi, produced in 1860 one of the earliest soil surveys within the United States with a report entitled “Geology and Agriculture”. George Nelson Coffey noted that most state geological surveys had engaged in soil mapping prior to the 1900s (1911).

Hilgard strongly advocated the creation of a joint agricultural and geological survey (Amundson and Yaalon, 1995). After Hilgard convinced the then director of the United States Geological Survey (USGS), John Wesley Powell, they worked to have the soil survey created within the USGS instead of the Department of Agriculture (USDA). Their view was summarized in a letter from Hilgard to Powell which described geologic mapping as the “indispensable basis to any really thorough work on the agricultural features; which are, primarily, the Quaternary geology of the region carried into detail and considered with reference to their bearing on agriculture” (Amundson and Yaalon, 1995). Hilgard and Powell eventually lost their bid for a joint geological and agricultural survey. The soil survey has since been a primarily agricultural endeavor. Despite the split in disciplines, modern applications of soil science and geology have found areas of mutual interest.

It would be difficult to construct a soil map without the context of parent material or geologic landform. The detailed field observations then provide valuable information for geologists. Ruhe’s (1969) and subsequently Burras and Scholtes’ (1987) work on the erosion of minor moraines in Iowa has been cited in geologic descriptions of the Des Moines Lobe (Quade et al., 2002). Brevik and Fenton (1998) integrated soil and geologic maps to improve the mapping of the Lake Agassiz Herman strandline. Lindholm (1994) used soil survey maps to create a detailed geologic map of an area in Hardy County, West Virginia for the identification of lithologies, slope, and landslide distribution.

The properties of the soil profile have significant influence on many environmental processes and hold evidence of past processes. The implementation of the soil survey with GIS allows a greater level of information to be managed with field delineations. Collaboration across disciplines could help determine the characteristics that would be the most beneficial for inclusion in the soil database. Although the inclusion of more information consistently across political boundaries would be advantageous, useful data can already be generated from existing soil maps. The soil survey can provide a finer scale resolution for material properties useful to other scientific studies.

Resources are usually limited for creating and field truthing Quaternary geology maps. The available Quaternary geology maps are generally large scale delineations of regions within a state. The soil survey has progressively increased the level of detail included in its mapping, but the soil survey attributes have been primarily agriculturally focused and used at the sub-county level. The recent implementation of the soil survey in a nation wide GIS format allows regional scale management and interpretation of the spatial data associated with the soil survey. By associating Quaternary geology interpretations, namely parent material, to soil map units, this research creates a Quaternary geology map on the regional scale with the level of detail available in the soil survey. The created map is compared with existing Quaternary geology maps for agreement and level of detail.

Methods

Description of Study Area

This study focuses on the southern Des Moines Lobe because it has a relatively simple morphology. This region is outlined by the Big Stone moraine in Minnesota to the north and the Bemis moraine extending from the Big Stone moraine to the present day city of Des Moines, Iowa (Figure 1). It is an area that has been glaciated within the past 14,000 years before present (Ruhe and Scholtes, 1959; Ruhe, 1969) and has a large boundary with a distinctive change between its till and an earlier loess parent material. The southern Des Moines Lobe

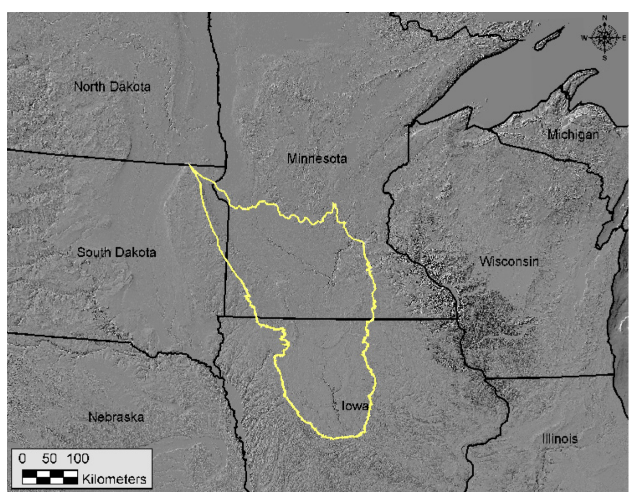


Figure 1. Hillshade map of region with southern Des Moines Lobe highlighted.

is primarily associated with the Clarion, Nicollet, Webster, Canisteo, and Okoboji soils. At the same time, its northeastern boundary offers some challenging tests.

There is some ambiguity about the relationship of Des Moines Lobe deposits around the Alexandria moraine of the Wadena Lobe. The area associated with the Pine City moraine northeast of the main Des Moines Lobe was not focused on because of its ambiguous relationship with the Bemis moraine and absence of the main soil association.

Creation of Categorized Soils Map

Digital soil maps of counties were obtained from the U.S. Department of Agriculture, Natural Resources Conservation Service's (USDA-NRCS) Soil Survey Geographic (SSURGO) Database (USDA-NRCS-1, 2005). Digital soil survey information was not available for Lincoln, Pipestone, Pope, Scott, Steele, and Stevens counties in Minnesota and therefore not able to be included in this study. Some additional counties outside the study region were included to provide a broader view in areas with multiple tills. In total, 80 counties were aggregated together for a combined map area of 140,343 km^2 (54,187 mi^2).

SSURGO is based on the National Cooperative Soil Survey (NCSS) produced by the NRCS-USDA Soil Survey Staff. Because the minimum soil delineation size in county surveys is around 6,000 m^2 (0.6 hectares), the maps are identified as 2nd order or Intensive soil surveys (Figure 2). To make this level of detail, the soil survey staff would identify soils in each delineation by field observations

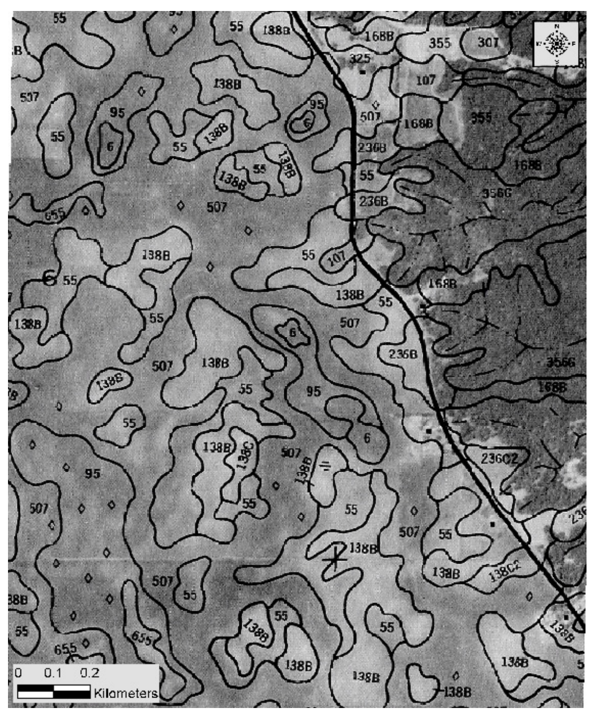


Figure 2. Example of soil survey map from which SSURGO is based.

and remotely sensed data. The boundaries are verified at closely spaced intervals (USDA-NRCS-2, 2005).

A database was constructed that categorized each soil name that appeared in the selected counties for Quaternary geologic attributes. Categorization was interpreted from the narrative soil descriptions available from the NRCS (USDA-NRCS-3, 2005). The category codes (Appendix A) were primarily based on parent material, but also included information about landscape position. This database was then linked to the SSURGO shapefile in ESRI's ArcGIS® 9.1 software. The map unit key, which was unique for each soil in every county, was used as the linking attribute. The final map was projected in zone 15 of the North American Datum (NAD) 1983 on the Universal Transverse Mercator (UTM) coordinate system. The soils were displayed by grouping categorized soils into 18 units of parent material.

Comparison with Existing Maps

In general, Quaternary geologic maps compile individual investigations using available remote sensing data for correlation. The Quaternary geology maps are then often field checked by county. Examples of such maps covering the southern Des Moines lobe are the 'Quaternary Geologic Map of the Des Moines 4˚ x 6˚ Quadrangle, United States' (Richmond et al, 1991) and the 'Geologic Map of Minnesota: Quaternary Geology' (Hobbs & Goebel (1982).

For spatial comparisons, only Quaternary geologic maps that were available in a GIS format were used to compare the categorized soil map for level of detail and agreement. A digital version of H.C. Hobbs and J.E. Goebel's 1:500,000 scale paper map 'Geologic Map of Minnesota: Quaternary Geology' was available from the Land Management Information Center, Minnesota Planning, and Minnesota Geological Survey (2005). In Iowa, a map of recognized moraines of the Des Moines Lobe from the Iowa Department of Natural Resources (1995) was the only available Quaternary geologic map available in GIS format. The Iowa DNR produced the map by digitizing Mylar maps produced by Tim Kemmis.

Results

Categorized Soils Map

The soil categorization produced a detailed map of the region's Quaternary geology (Figure 3). Diverse parent materials associated with glacial lakes, outwash, and ground moraines can be seen clearly. Holocene deposits of alluvium can be distinguished in river valleys and the swales between ground moraines. Although not prevalent in this landscape, rock outcrops can also be identified.

Viewing this map at a large scale made it necessary to group information that was available in the soil survey. More detailed information, such as the type of rock for outcrops, is included with the soil survey description and maintained in the category codes created for this study. Landscape position was also coded into this categorization. This could be useful in smaller scale studies where the shape of the land provides important information. Landscape positions included slope positions, terraces, and concave or convex shape.

Figure 4 demonstrates the level of detail present in this categorization of the soil map. Instead of generalized regions, intertwined deposits can be viewed in relationship to one another. The glacial outwash, which would have flowed through lower areas, can be seen as flowing from the moraine margin and laterally wrapping around the features higher than the level of flow. The material of the Iowa Erosion Surface is described by the soil survey as loamy sediments. These loamy sediments can be found with islands of till deposits on the eastern edge of the Des Moines Lobe. With this representation, it is not difficult to imagine the theory that the Iowa Erosion Surface was the product of the glacier position creating a

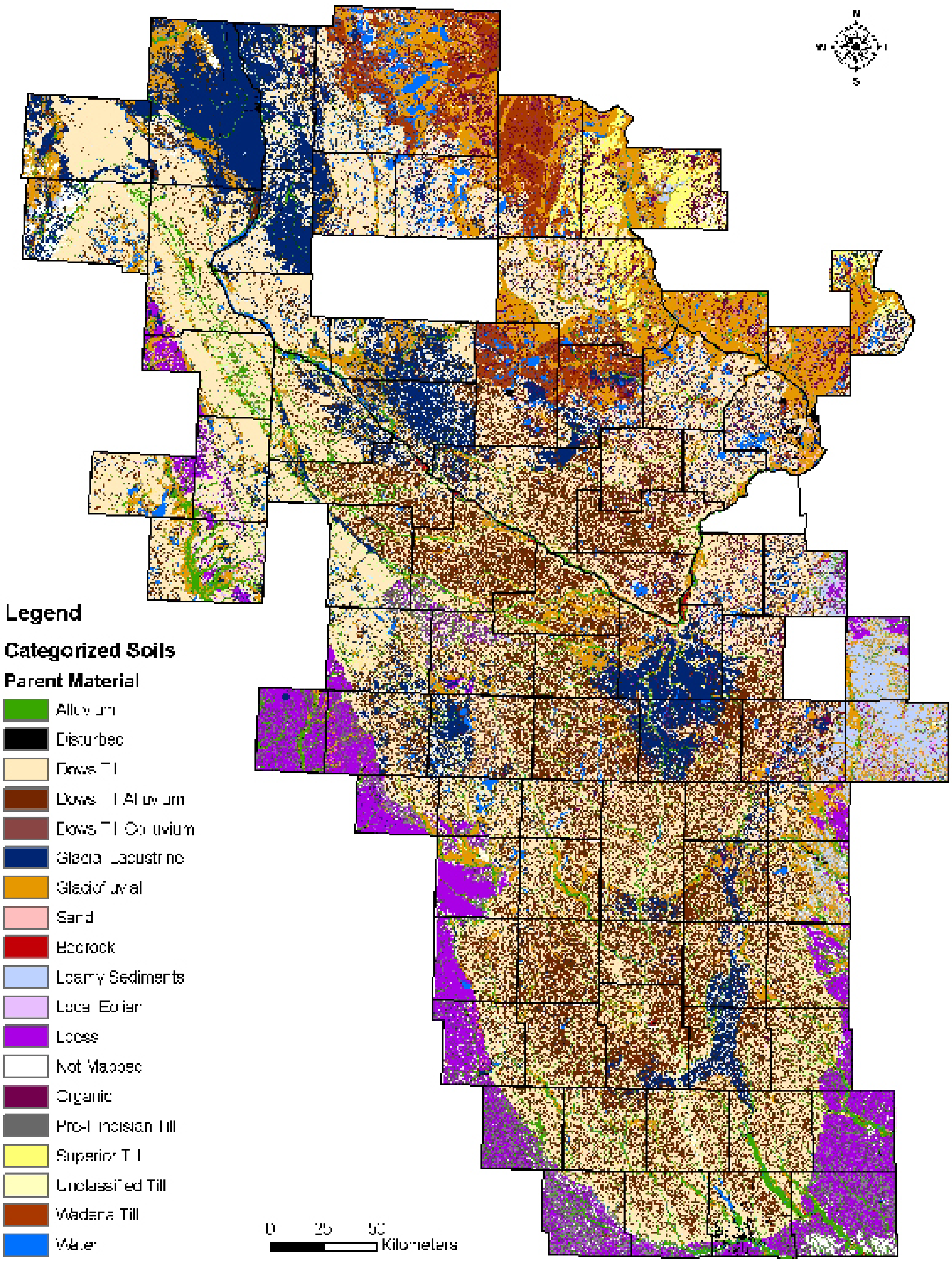
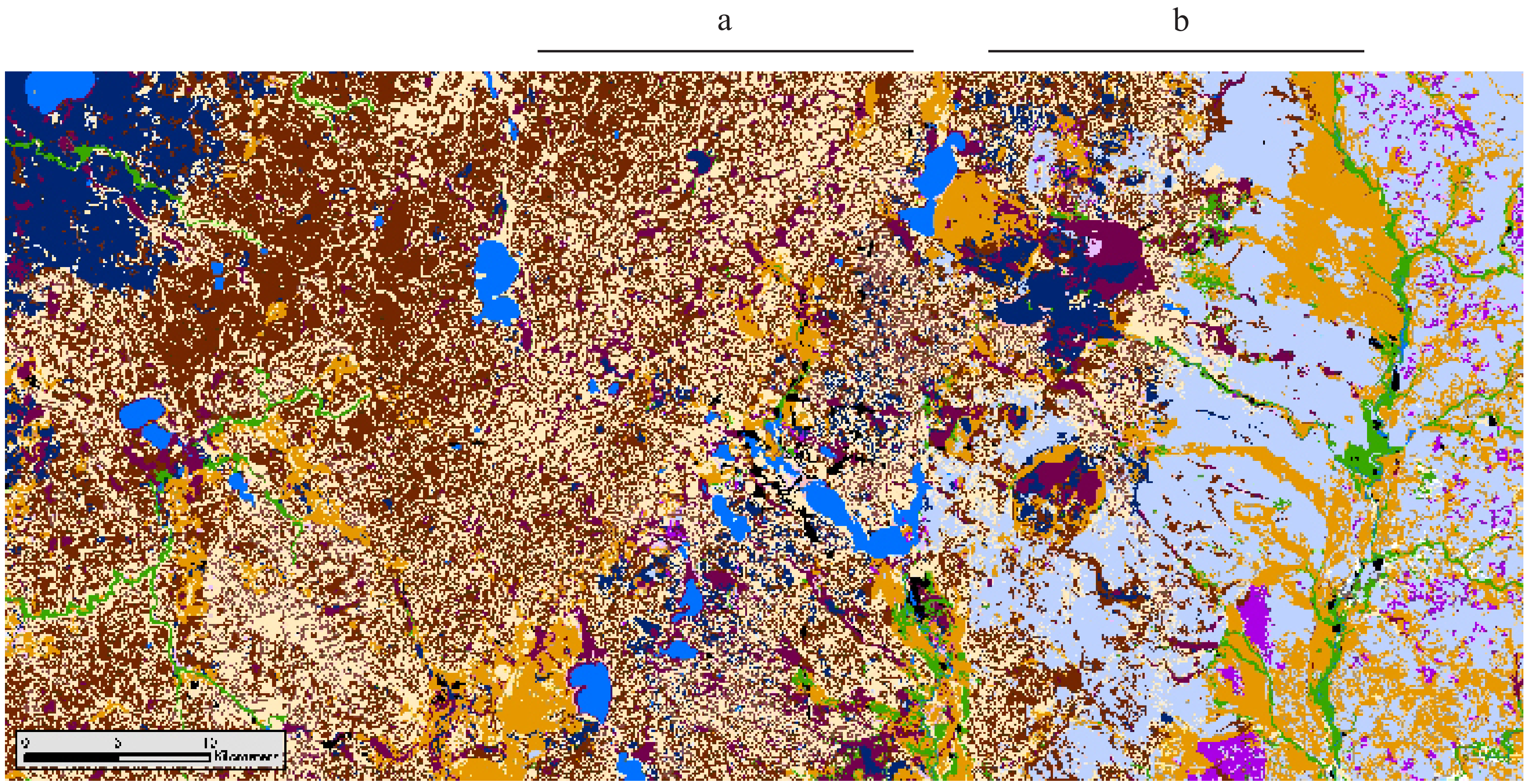


Figure 3. Quaternary geologic map of the Des Moines Lobe in Iowa & Minnesota produced by categorizing soil map units and linking with SSURGO shapefiles.



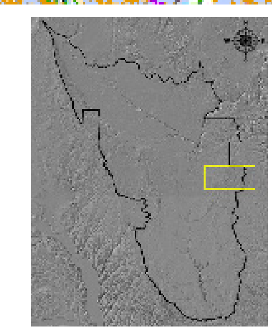


Figure 4. Example of detail shown by categorized soil map (see legend from Figure 3). Note the stagnation moraine features behind the Algona moraine (a) and the eroded edge of the Des Moines Lobe intertwined with the loamy sediments of the Iowa Erosion Surface (b).

harsher climate to its east. Advanced erosional processes can be seen to have removed loess from the area beyond the Des Moines lobe and till deposited earlier by the Des Moines Lobe.

The topography could be inferred from soil landscape positions describing the concave or convex shape. On the Des Moines Lobe till that is not necessary, because of the ability to differentiate alluvium that has accumulated in the swales. The concentric patterns of stagnation moraine can be seen in the north central part of Figure 4. In other parts of the Des Lobe, ground moraine can be seen by the parallel lines of alternating till and alluvium derived from till.

Enhancing Map with Elevation Hillshade

The level of detail available in the categorized soils map is complemented by a hillshade derived from a digital elevation model. The combined data sets allow geologic features to appear more clearly (Figure 5). The nature of floodplains to be a flat area within stream valleys is illustrated by this representation. The juxtaposition of Pre-Illinoisan till under Wisconsinan Loess and then exposed by the cutting of stream networks is also displayed by the combination of the categorized soils map with an elevation hillshade.

Large Extent Comparison for Agreement

To check for agreement between the two maps, the line delineations of the Minnesota Quaternary geology map and the Des Moines Lobe map were overlaid on top of the categorized soils map (Figure 6). The geology maps for both states show overall agreement with the soil map. The expected boundaries between major parent material changes coincide nearly all of the time. The level of agreement is illustrated by the matching areas where there are pockets of Des Moines Lobe till, Wadena Lobe till, and outwash in north central Minnesota.

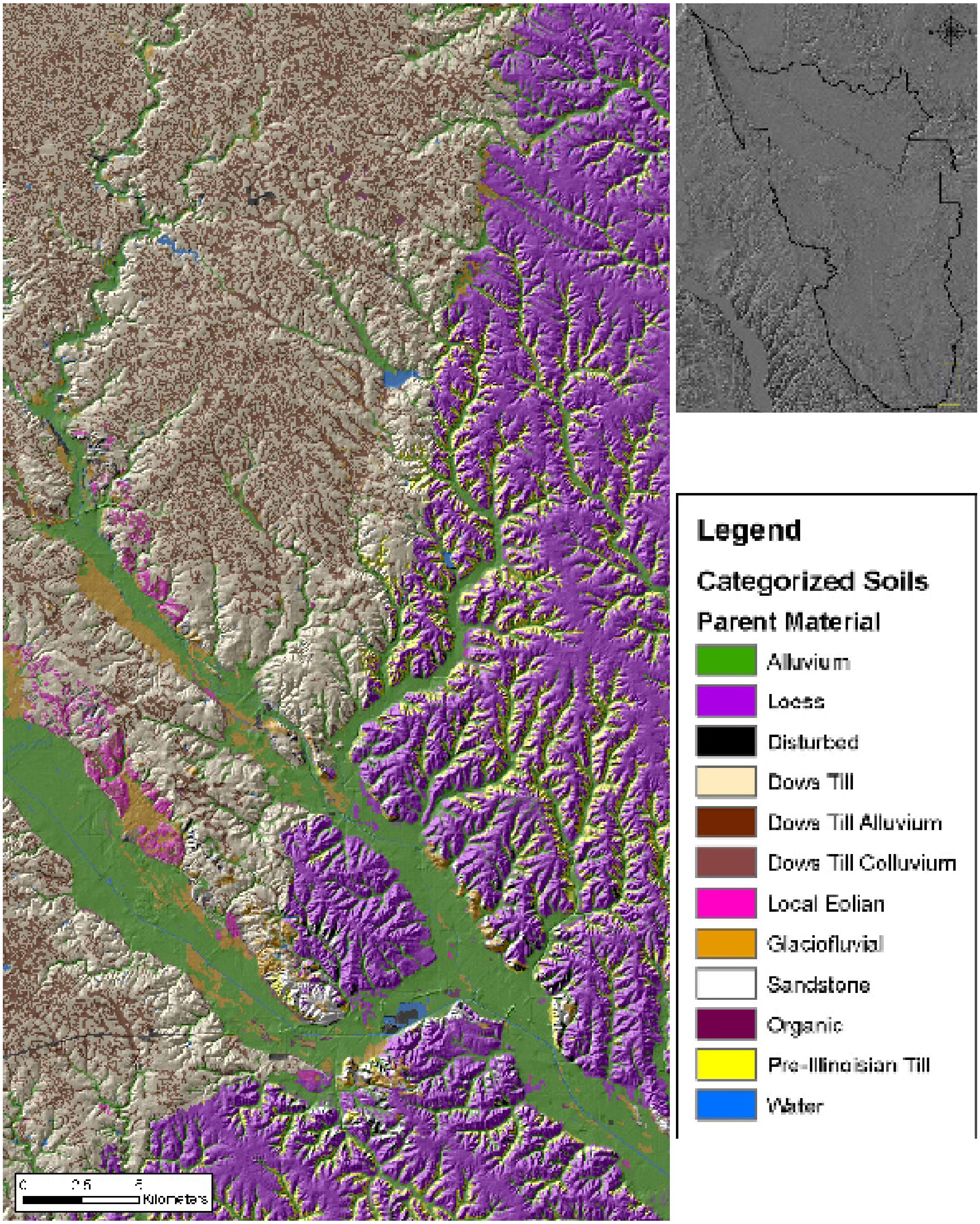


Figure 5. The elevation hillshade was overlaid with the categorized soils map to enhance visualization of geologic features. Notice the local eolian deposits on the east side of the floodplains and the sandstone outcrops (south). The juxtaposition of Pre-Illinoisan till exposed by the stream network from under Wisconsinan Loess can also be seen (east).

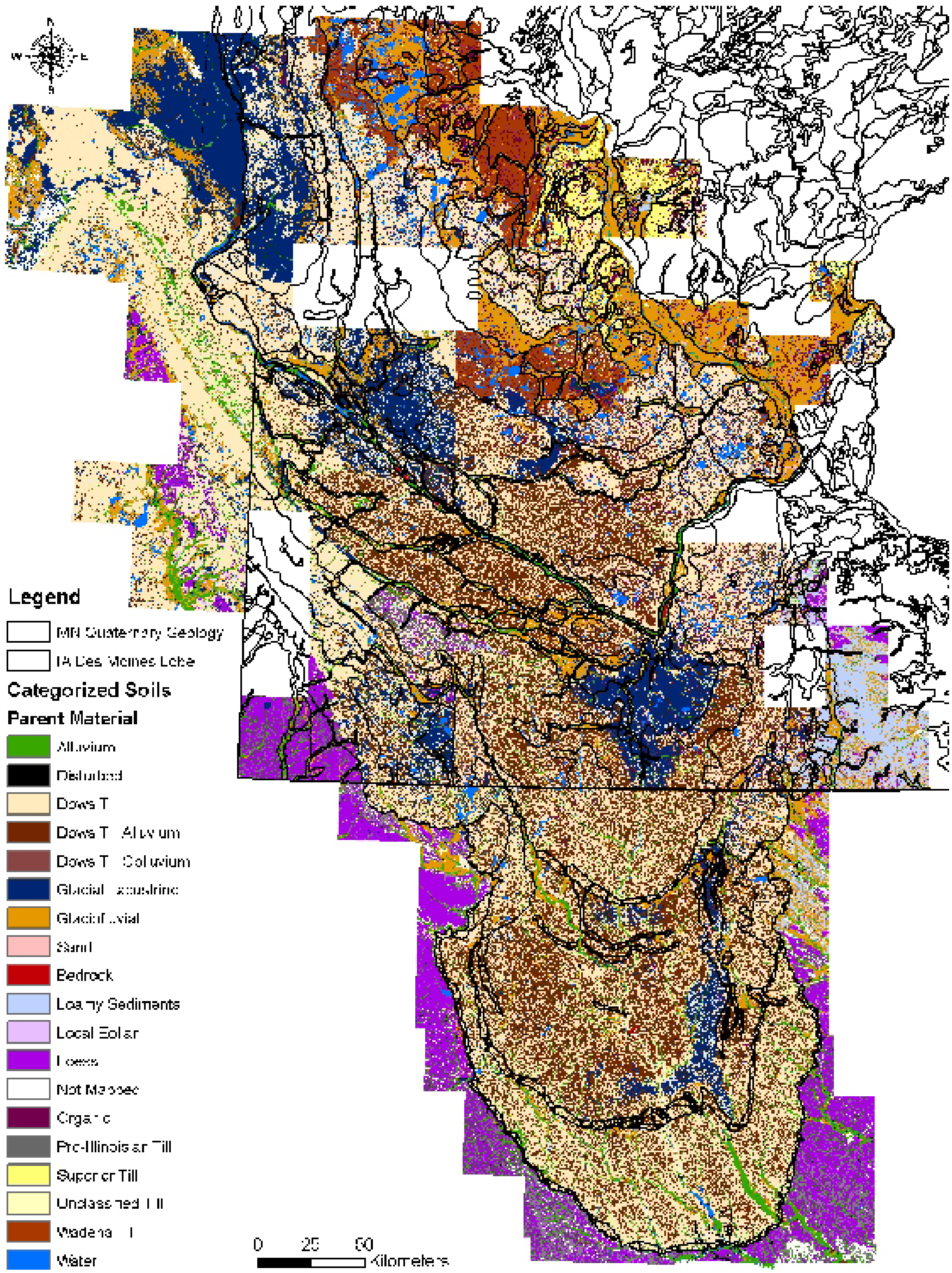


Figure 6. General overlay of Quaternary geologic maps on categorized soil map. General delineations of the Quaternary geologic map usually matches soil parent material. The exception is a county line in central Minnesota where the soil map stops showing the Wadena till to the west and the glacial lake does not show to the east.

In Minnesota, the Quaternary geologic map includes delineations of outwash, glacial lakes, ground moraine, and stagnation moraine. The Quaternary geologic map and the categorized soils map agree on most areas of outwash flow. The soil map shows some differences in the extents of glaciolacustrine parent material. Delineation of ground moraine and stagnation moraine are difficult because of the gradual transition between the two. Areas identified by the Quaternary geologic map as predominantly stagnation moraine roughly coincide with stagnation moraine features visible in the soils map.

A similar Quaternary geologic map of Iowa was created by Richmond et al (1991). However, the Iowa Des Moines Lobe map was the only Quaternary geologic map found for the Iowa area in a GIS form. Since this map was only intended to map the major moraines it can be used to check general agreement, but is not a fair comparison of detail. In this comparison the geologic delineation of the Des Moines Lobe shows close agreement with the parent material boundary observed by the soil survey.

A major benefit from representing parent material in fine detail with color coded delineations is the ability to show the intermixed relationship of formations. Large scale maps must delineate by spatial majority groups. Fine scale maps with appropriate groupings in the legend can still be viewed at a large scale and provide more information about the landscape.

Small Extent Comparison for Agreement

The same approach was used for a smaller section of the Minnesota maps (Figure 7). The two smaller scale maps still show generally close agreement, particularly in the fluvial environments of glacial outwash and modern floodplain alluvium. The small islands of Superior Lobe end moraine also have close agreement from the two maps. The categorized soils map shows larger areas for both glacial lakes included in this smaller-scale comparison.

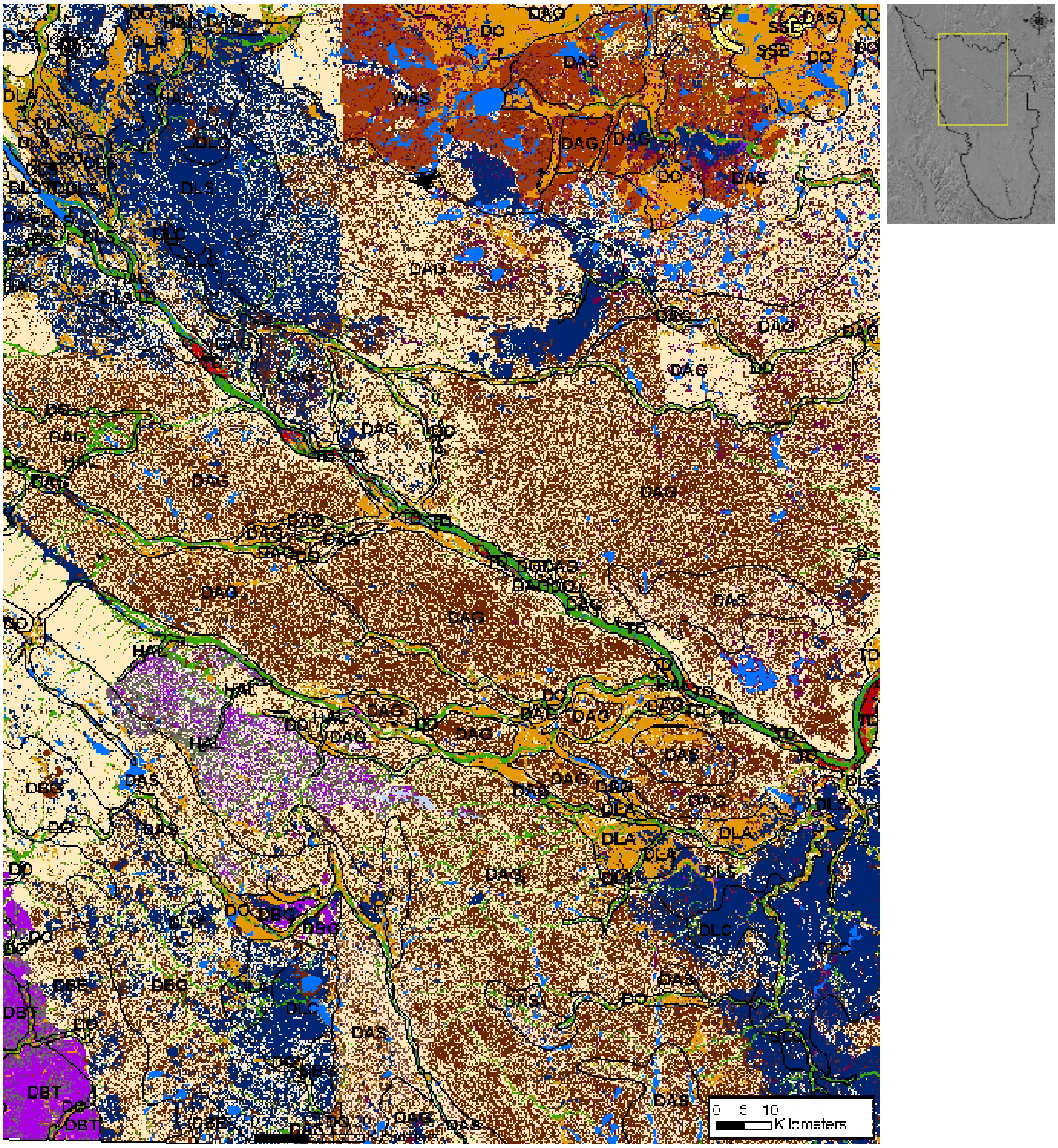


Figure 7. (See Table 1 for Quaternary map symbols) Delineations of the Quaternary geologic map overlaid on the categorized soil map. Items to Note: the soil mapping of loess on the Bemis terminal moraine (SW corner), the exposure of loess and Pre-Illinoisan till in an area of Altamont ground moraine (S center), difference in extent of the glacial lakes (SE corner & NW corner), and disagreement of county soil surveys observed by anthropogenic line (N center).

Delineation of the transition between stagnation moraine and ground moraine can be difficult in many areas. The categorized soils map displays the individual features which show the main areas of stagnation moraine and the gradient of landform shape to ground moraine. Although there is general agreement, the concentration of stagnation moraine features often extends beyond areas delineated by the Quaternary geologic map.

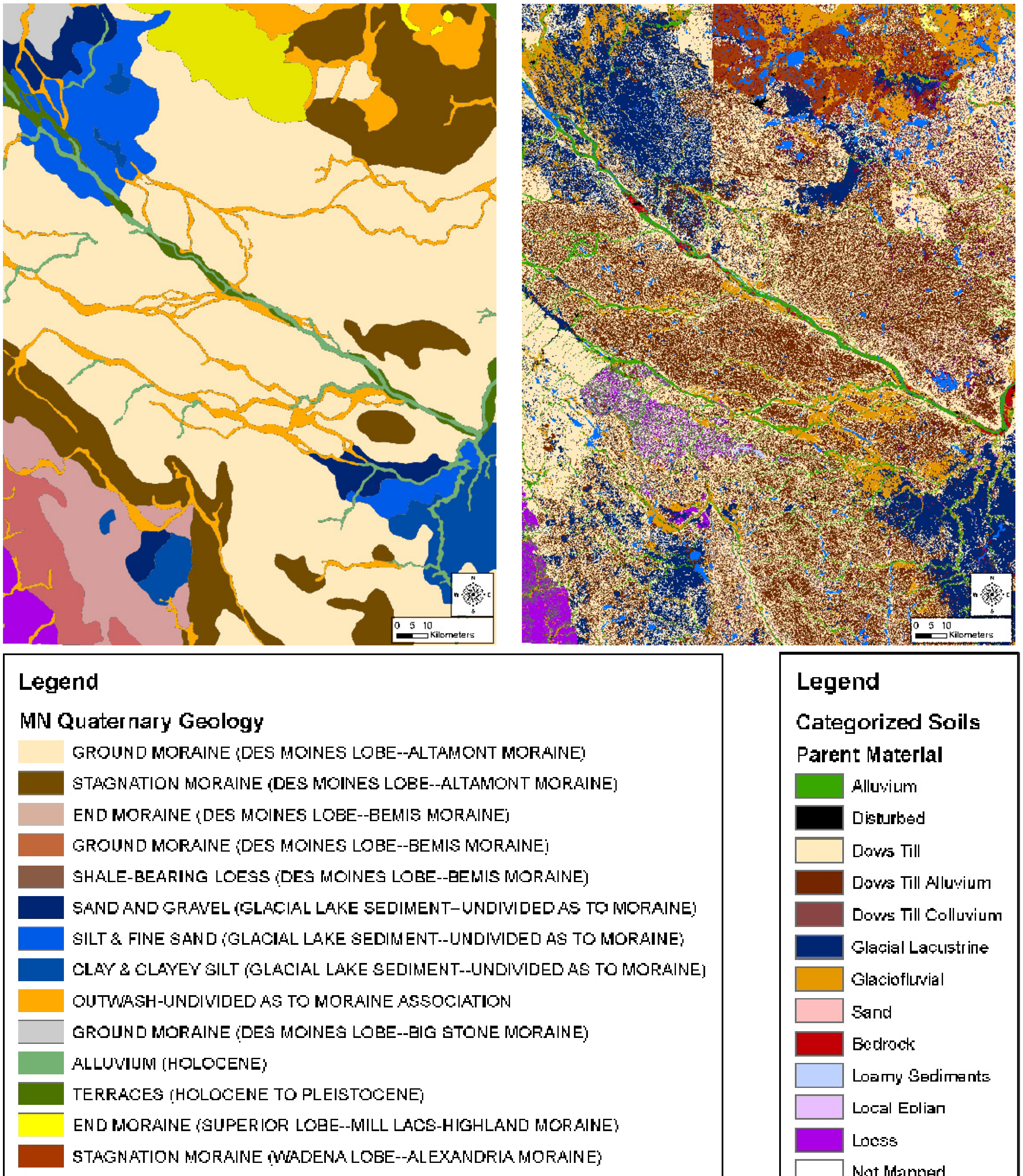
Table 1. Abbreviations used for Minnesota Quaternary geologic map.

Code	Description
DAG	Altamont Ground Moraine (Des Moines Lobe)
DAS	Altamont Stagnation Moraine (Des Moines Lobe)
DBE	Bemis End Moraine (Des Moines Lobe)
DBT	Shale-bearing Loess, Bemis Moraine (Des Moines Lobe)
DLA	Sand & Gravel (undivided as to moraine)
DLC	Glacial Lake Sediment (undivided as to moraine)
DLS	Silt, Fine Sand (undivided as to moraine)
DO	Outwash (undivided as to moraine)
DSG	Big Stone Stagnation Moraine (Des Moines Lobe)
HAL	Holocene Alluvium
SSE	Mill Lacs End Moraine (Superior Lobe)
TD	Terraces (Holocene to Pleistocene)
WAS	Alexandria Stagnation Moraine (Wadena Lobe)

Comparison for Level of Detail

The same area of Minnesota used for the small scale agreement comparison was used for a detail comparison (Figure 8). The Quaternary geology map distinguishes between deposits associated with the major moraines of the Des Moines Lobe. Information in the soil survey did allow for the differentiation of these areas because they are all associated with the same till. The Quaternary geology map delineates three grades of glaciolacustrine sediments, where this categorization of soils was only able to discern glaciolacustrine origin.

Disagreement between county soil surveys can be seen in several places. The glacial lake in the northwest corner of the map has a common eastern border with a county line. The same county line to the north maps deposits from the Wadena Lobe ending abruptly west of the line.



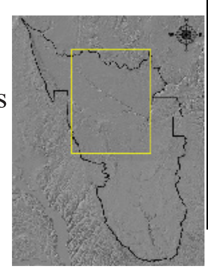


Figure 8. Side by side comparison of the Minnesota Quaternary geologic map (left) and the categorized soils map (right). In the categorized soils map, bedrock exposures can be seen along the Minnesota River and a greater extent of the Alexandria moraine is mapped. The Quaternary geology map includes the differentiation of three textures of lacustrine sediments that the categorized soil map does not.

The categorized soils map overall shows more detail. For example, small areas of bedrock outcrops can be seen in the Minnesota River valley. The categorized soils map also shows some additional features not shown in the Quaternary geology map. The soils map shows the extent of the Alexandria moraine extending further east. The soils map also shows a large exposure area of Wisconsinan Loess and Pre-Illinoisan till in the southwest corner of Minnesota.

Discussion

Differences in interpretation between soil correlations can provide some irregular results between counties. One notable difference can be seen as a line separating Minnesota and Iowa (Figure 3). The Minnesota side appears darker at the regional scale because of generally larger soil delineations (Figure 9b). The larger delineations in the southern tier counties of Minnesota result in larger areas of soils classified as Dows till alluvium. Zooming in on the Minnesota/Iowa border demonstrates the continuity that is still present between different surveys (Figure 9c). The difference at the states' border appears to be primarily due to the level of detail used in the delineations. The difference in soil delineation is only noticeable for the southern tier of counties in Minnesota. The size of soil delineations decreases to the north, regaining the detail seen in Iowa.

There are instances where the geologic map and the soil map disagree about the extent of a geologic feature. For example, according to the soil map the glacial lake in south central Minnesota has associated parent material extending farther south than shown by the geologic map. It is difficult to judge from this investigation which is correct. Field ground-truthing is the only way to verify which is correct. The soil survey has the benefit of extensive field observations to correlate similar materials. Although the soil surveyors did not have geologic mapping responsibilities when they created the soil map, their field observations lend credibility to their delineations.

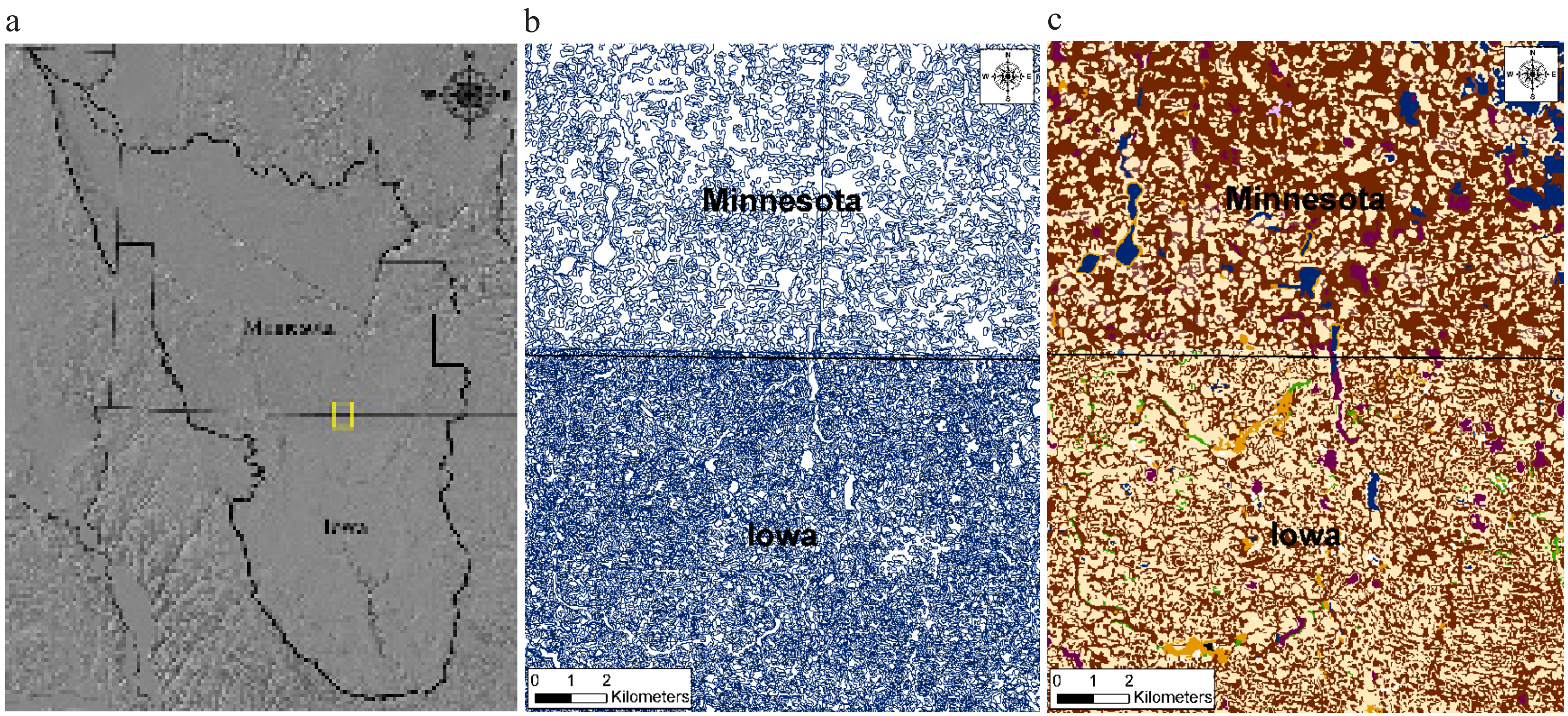


Figure 9. a) Area used in example. b) Soil delineations showing the difference in detail included by the two respective counties. c) Same area color coded by parent material demonstrating continuity of delineation borders.

Compiling county soil maps together for regional assessments does have some limitations. Each county is surveyed at different times and often by different people. The county level focus of the survey introduces some impractical divisions in soil property mapping. This can be seen in the glacial lake below the Big Stone moraine in central Minnesota. By the soil map, the lake has a linear eastern boundary that coincides with the county line. This is unlikely to be the true shape of this lake. County surveys that evaluate their mapping with both field observations and in context with surrounding counties can alleviate much of this problem.

It should be noted that the original GIS soil map produced by Iowa, the Iowa Soil Properties and Interpretations Database (ISPAID), included information about parent material. That attribute did not put the parent material in as much of a geological context as this categorization has, but still provided much of the information needed for Quaternary geologic mapping. The national SSURGO digital soil map has superseded Iowa's ISPAID digital soil map. In SSURGO it is unclear what information will eventually be added to associated databases. Attribute tables for SSURGO are developing differently for each state. The great advantage of GIS is that attributes to spatial data can be added at any time by correlating with an identification field in the SSURGO map.

Conclusions

Categorization of soil map units with respect to parent material appears to have successfully created a detailed Quaternary geologic map and warrants further validation. The focus of soil surveys on county level surveys does create some limitations in regional continuity. However, the categorized soil map overall qualitatively shows close agreement with the existing Quaternary geologic maps with an added level of resolution.

Differences between existing quaternary geology maps and categorizing soil maps occur. Use of soils maps for Quaternary geology need to be used in reference to existing

Quaternary geology maps because of the occasional disagreements between the two maps. Increased dialog between the two disciplines could help resolve these differences and perhaps answer questions that have remained for both groups. For example, the level of detail surveyed by soil scientists could help geologists decipher ambiguous or complicated areas of multiple glacial advances.

After the development of keys that relate soil survey terminology to information of geological interest, the use of the soil survey can be a quick and easy reference for geological inquiry. The same concept applies to any discipline affected by soil properties. Within the soil survey, soil names are expected to consistently describe a defined range of soil properties. Those definitions can be used to create a spatially linked database for the attributes of interest. In the future, other soil properties could be added and studied spatially at practically any scale.

References

Amundson, R. and D.H. Yaalon. 1995. History of soil science: E.W. Hilgard and John Wesley Powell: Efforts for a joint agricultural and geological survey. *Soil Science Society of America Journal*. 59:4-13.

Brevik, E.C. and T.E. Fenton. 1999. Improved mapping of the lake Agassiz Herman strandline by integrating geological and soil maps. *Journal of Paleolimnology*. 22:253-257.

Burras, C.L. and W.H. Scholtes. 1987. Basin properties and postglacial erosion rates of minor moraines in Iowa. *Soil Science Society of America Journal*. 51:1541-1547.

Coffey, G.N. 1911. The development of soil survey work in the United States with a brief reference to foreign countries. *Proceedings of the American Society of Agronomy*. 3:115-129.

Hilgard, E.W. 1860. Report on the geology and agriculture of the state of Mississippi. State Printer. Jackson, Mississippi.

Hobbs, J.C. and J.E. Goebel, 1982. Geologic map of Minnesota: surficial geology. Minnesota Geological Survey Map S-1.

Iowa Geological Survey, Department of Natural Resources. 1995. The Des Moines Lobe and it's glacial advances in Iowa. [Online] Available: http://www.igsb.uiowa.edu/nrgislibx/.

Lindholm, R.C. 1994. Information derived from soil maps: areal distribution of bedrock landslide distribution and slope steepness. *Environmental Geology*. 23:271-275.

Land Management Information Center, Minnesota Planning, and Minnesota Geological Survey. 2005. Geologic map of Minnesota: Quaternary geology, from MGS (Map S-1), 1982 (Digital Version). [Online] Available: http://www.lmic.state.mn.us/chouse/metadata/quatgeo.html.

Quade, D.J., Giglierano, J.D., E.A. Bettis III, R.J. Wisner. 2002. Surficial geologic gap of the Des Moines Lobe of Iowa. Iowa Geological Survey.

Richmond, G.M. (ed.), D.S. Fullerton (ed.), A.C. Christiansen (ed.), G.R. Hallberg (comp.), J.A. Lineback (comp.), D.M. Mickelson (comp.), J.C. Knox (comp.), J.E. Goebel (comp.), H.C. Hobbs (comp.), J.W. Whitfield (comp.), R.A. Ward (comp.), J.D. Boellstorf (comp.), J.B. Swinehart (comp.), and V.H. Dreeszen (comp.), 1991. Quaternary geologic map of the Des Moines 4˚ x 6˚ Quadrangle, United States: U.S. Geological Survey Miscellaneous Investigations Series I-1420 (NK-15). Denver, Colorado: U.S. Geological Survey.

Ruhe, R.V. 1969. Quaternary landscapes in Iowa. Iowa State University Press, Ames, IA.

Ruhe, R.V. and W.H. Scholtes. 1959. Important elements in the classification of the Wisconsinan glacial stage. *Journal of Geology*. 67:585-593.

U.S. Department of Agriculture, Natural Resources Conservation Service, 2005-1, 2005. Soil survey geographic (SSURGO) database. [Online] Available: http://www.ncgc.nrcs.usda.gov/products/datasets/ssurgo/.

U.S. Department of Agriculture, Natural Resources Conservation Service-2, 2005. National soil survey handbook, title 430-VI. [Online] Available: http://soils.usda.gov/technical/handbook/ .

U.S. Department of Agriculture, Natural Resources Conservation Service-3, 2005. Official soil series descriptions (OSD). [Online] Available: http://soils.usda.gov/technical/classification/osd/.

CHAPTER 2. SPATIAL PATTERNS OF HISTORICAL DEPRESSIONAL WETLANDS AND RESPECTIVE WATER BUDGETS IN THE DES MOINES LOBE OF IOWA

A paper to be submitted to the Journal of Environmental Quality

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Abstract

The drainage of the Des Moines Lobe in Iowa occurred prior to most documentation on the extent and hydrologic function of pothole wetlands. This study reconstructed information about the pre-settlement condition of pothole wetlands from soil survey maps and a digital elevation model (DEM). Historical depressional wetlands could be delineated with soil survey maps because of soil properties that result from wetland conditions. The wetland's watersheds were delineated with the DEM. The watershed to wetland area ratio was used as an indicator of the wetland's water budget and compared with trends of precipitation, evaporation, and geologic landform.

The comparison of mapped existing wetlands in the National Wetland Inventory showed that 98.5% of the depressional wetland area has been drained from the Des Moines Lobe of Iowa. Despite the potential of landscape to influence the watershed to wetland area ratio, climate showed a generally smooth trend. Of the climate components, evaporation shows the strongest effect. This illustrates the dominant role that evaporation has in the hydrology of depressional wetlands and this landscape.

Introduction

The prairie pothole region is recognized as an area of some 770,000 km^2 extending from Alberta to north central Iowa that is characterized by depressional wetlands. Those wetlands have been associated with producing between 50% and 80% of North Americas waterfowl (Batt et al., 1989). Emergent macrophytes comprise the dominant vegetation, although vegetation structure varies as a function of wetland depth and size (van der Valk and Davis, 1978).

A depressional wetland's size is the product of its water budget as a function of its watershed area and climate conditions. Depressional wetlands are unique in that their natural hydrology is mostly isolated from stream networks. Past studies of depressional wetlands have found that direct rainfall, watershed runoff, and evapotranspiration are the primary components of their water budget (Shjeflo, 1968; Sloan, 1972). In this paper, the term watershed refers to the hydrological capture area of a depressional wetland. Watershed to wetland area ratios are then indicative of depressional wetlands' water budgets. Galatowitsch and van der Valk (1993) recognized this relationship and used watershed to wetland area ratios to predict water regimes of restored wetlands.

The southern Des Moines Lobe is of interest because it is the intersection between this wetland region and where agricultural drainage has been the most extensive. Historical documentation refers to the southern Des Moines Lobe area as an area of vast swamps (Beauchamp, 1987). This region has since been almost completely drained. The majority of that drainage happened around the 1900s, leaving behind little information about the extent of the wetlands before settlement. As far as the author is aware, a regional method of reconstructing the location, area, and hydrologic properties of these wetlands is not available.

The hydrology that determines vegetation characteristics also causes soil characteristics that persist long after artificial drainage (Galatowitsch and van der Valk, 1994). Therefore, soil surveys can be used to estimate wetland extent before drainage and cultivation (Hewes, 1951). This research locates soil delineations associated with historical depressional wetland conditions. It then estimates the historical wetland areas and their watershed areas for the purpose of calculating watershed to wetland area ratios. The watershed to wetland area ratios are then analyzed for patterns influencing the wetlands' water budget.

Methods

Description of Study Area

For this study, the Des Moines Lobe is defined as the extent of soils associated with the Clarion, Nicollet, Webster, Canisteo, and Okoboji soils in Iowa (Figure 1). These soils are associated with the southern region of the Des Moines lobe parent material. This region is outlined by the Bemis moraine extending from Iowa's northern border to the present day city of Des Moines, Iowa. This section of the Des Moines Lobe was chosen because it is the area of the prairie pothole region that has been the most extensively drained.

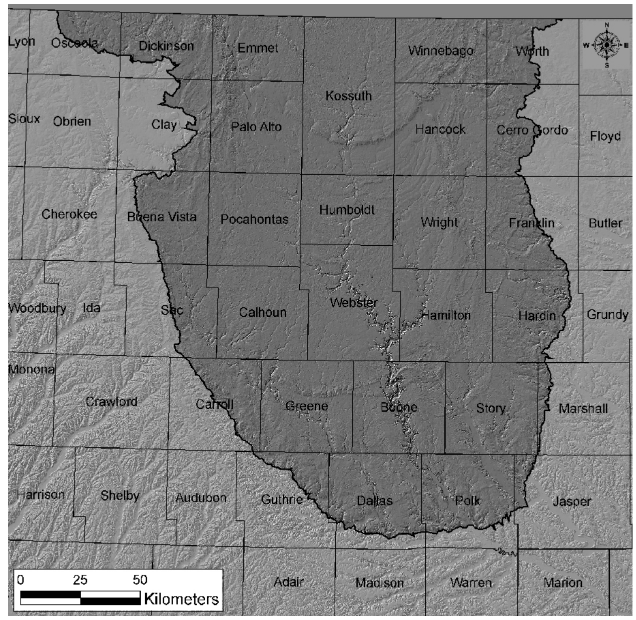

Figure 1. Extent of Des Moines Lobe in Iowa

Identification of Depressions

To identify historical, depressional wetlands, it is assumed that certain soils can be used to delineate wetlands, even many decades after being drained. Soil survey maps are detailed representations of landscape characteristics. They indicate long-term environmental conditions on a given parent material. Not all depressions will be associated with soils classically identified as pothole wetland soils. Understanding of the watershed's morphology is required to identify depressions that have different soil characteristics due to changing environmental conditions, but are still indicative of historical depressional wetlands. The Soil Survey can provide a field-observed data set when concepts of soil morphology are applied.

There is a functional relationship between soil formation factors and soil properties. The factors identified by Jenny (1941) are climate, organisms, relief, parent material, and time. Water is an important force that is included in both climate and relief. The characteristics and spatial patterns of the soils then give us important clues to the historic hydrology.

Differences in relief result in differences in soil type because the differences in the soil position in relation to relief result in differences in local soil climate. Local variations in topographical position will result in unique soil climates (Ellis, 1938). In the case of depressional wetlands, there would be a very wet soil climate. If the precipitation on a given section of land is 80 cm per year, the soils on the knolls will receive 80 cm minus the amount that runs off. Therefore, the soils on the knolls will have a locally arid soil climate in comparison with regional normal soils. On the other hand, the soils of the depressions will receive 80 cm of precipitation plus the amount of water that runs off from the adjacent higher lands (Figure 2). Therefore, more water will penetrate into or pond on the soils in the lower position.

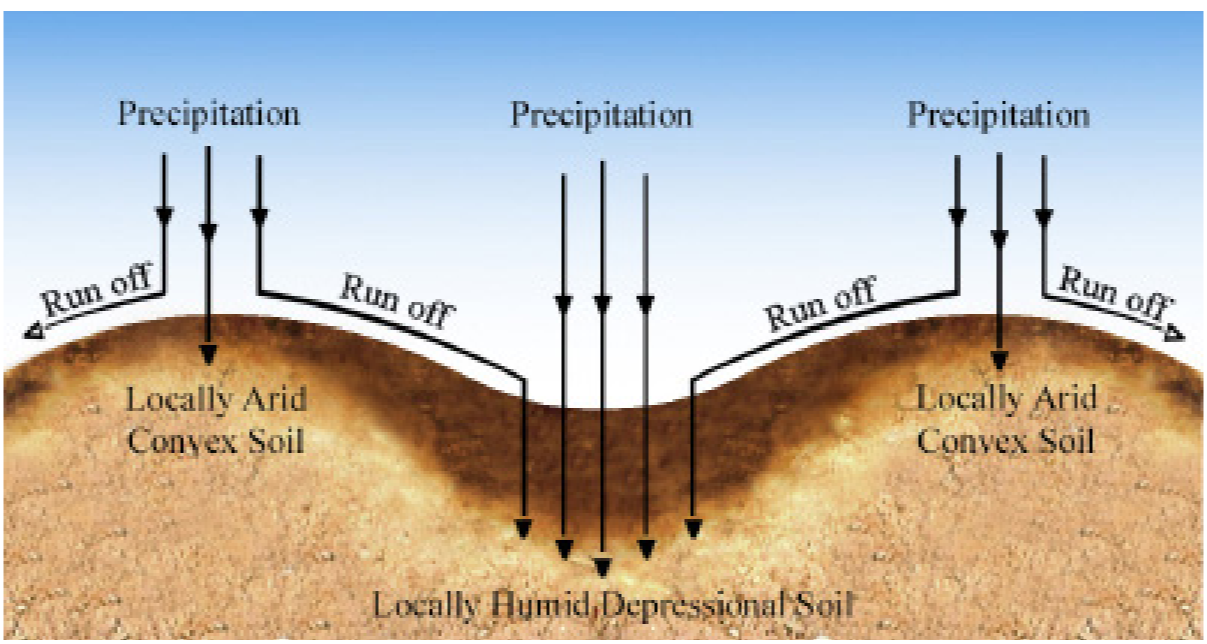

Figure 2. Effect of relief on water penetration of soils (modified from Ellis, 1938).

In the center of many depressions water saturation conditions produce soils that generally exhibit a gleyed horizon and an abundant accumulation of organic matter. These are all indicators of long term water saturation coinciding with the existence of a wetland. Accumulation of organic matter can be identified by deep dark layers which occur when water saturation causes anaerobic conditions that suppress decomposition. The anaerobic conditions also cause the reduced state of soil minerals, producing a gleyed chroma (Khan & Fenton, 1994; Vepraskas, 1994; Richards & Vepraskas; 2001). Soils having these characteristics indicate long term ponding and the long term average of a wetland's extent. Even if this soil is examined during a dry period or after drainage it will still have many of the properties corresponding to soil formation factors. For this study, it is necessary to assume that the delineations in the soil survey still reflect pre-agricultural conditions.

Digital soil maps were obtained from the Natural Resources Conservation Service's (NRCS) Soil Survey Geographic (SSURGO) Database (USDA-NRCS-1, 2005). The available county soil maps were merged into one coverage and classified for the likelihood of being an upland depressional wetland (Appendix B).

Soil characteristics were interpreted from the Official Soil Series Description available from the NRCS (USDA-NRCS-2, 2005). The first type of soils identified as depressional wetlands were those whose descriptions fully characterized upland, pothole wetland soils such as Okoboji, Knoke, and Palms. These soils are most easily identified in the 'geographic setting' section of the series description. Terms such as depressional and closed depression are the clearest identifiers. If the description only refers to the soil as concave, further investigation is required to distinguish it from a swale soil. The 'drainage and permeability' section can offer important clues about ponding of water. The 'typical pedon' description offers supporting evidence if the profile shows signs of anaerobic conditions, such as an accumulating organic horizon or gleyed chromas. The descriptive information is taken into consideration with examination of examples from the soil survey maps overlaid on an elevation hillshade generated from a digital elevation model (DEM). Taken together, this information provides a reasonable assessment of which soils are long-term, depressional wetlands.

Depressional wetlands are ephemeral in nature and fluctuate considerably in areal extent (van der Valk and Davis, 1978). In many cases, this creates a condition where there is a core wetland soil and a border soil. The border soil shows some evidence of elevated water interaction, but lacks the full degree of signs indicating long-term water ponding. An example of this type of soil in the Des Moines lobe is the Harps soil. It has a general accumulation of calcium carbonate because of the dominant evaporation of sub-surface water, instead of the dominance of water ponding. Evaporation leaves the minerals that were held in solution behind on the soil. The Harps soil is often found surrounding established depressional wetland soils. The Harps soil also sometimes appears to be without a wetland soil in the middle. When the Harps soil occurs alone, it is still indicative of the same topographical conditions. The only difference is that water does not pond in the center for a long enough period to produce the more traditional wetland soil.

Iowa's Soil Properties and Interpretational Database (ISPAID) includes a point data set of soil inclusions that were too small to be delineated. The spot coverage shows many inclusions of soils, such as Okoboji, in areas that should be included as depressional wetlands. The reason for them being spot coverages and not being delineated is because of their small areal size. However, most of the spot locations for depressional soils are accounted for by inclusion within the depressional border soils (Figure 3). The inclusion of both groups accounts for buffering around larger depressional complexes, depressions with wetland soils too small for delineation, and depressions that no longer hold enough water to exhibit full wetland soil characteristics.

The database of depressional categories was linked with the SSURGO shapefile. In GIS, spatial information can be linked to attribute information with a common identification

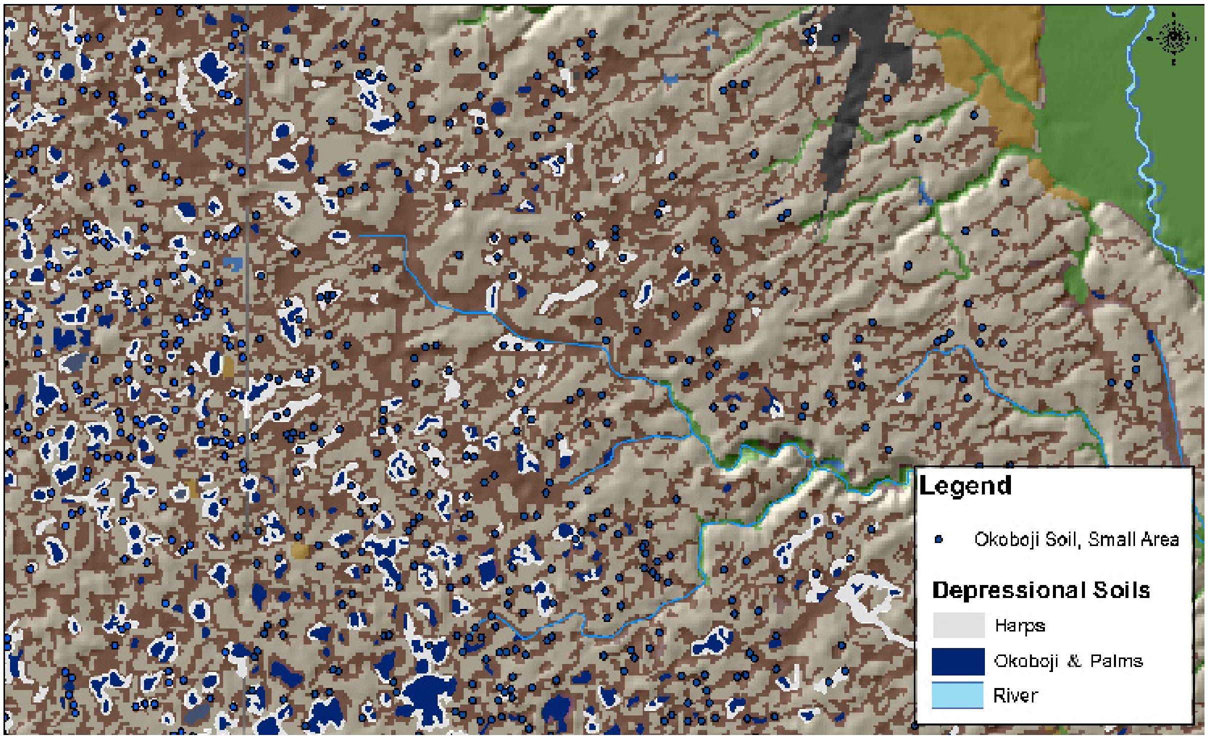

Figure 3. Map of Walnut Creek in Story County, IA. Identified wetland core and border soils are displayed with point locations of inclusions.

field. The map unit key, which was unique for each soil in every county, was used as the linking attribute. All delineations that could represent depressions including those that were classified as water were selected and exported to a new shapefile.

The possible depression map was then visually screened for accuracy. Identified delineations were checked against aerial orthophotos to both insure that man-made structures were not included and that most visually apparent depressional wetlands were included. The majority of removed delineations were water map units that delineated reservoirs, quarries, rivers, riparian wetlands, and large connected lakes. Soil units that were out of place or had an organic parent material were those most commonly removed from floodplain areas. Soils having descriptions indicating upland formation were sometimes found in floodplain areas. Soils classified with an organic parent material are not defined by a landscape position and were removed when found in floodplain areas.

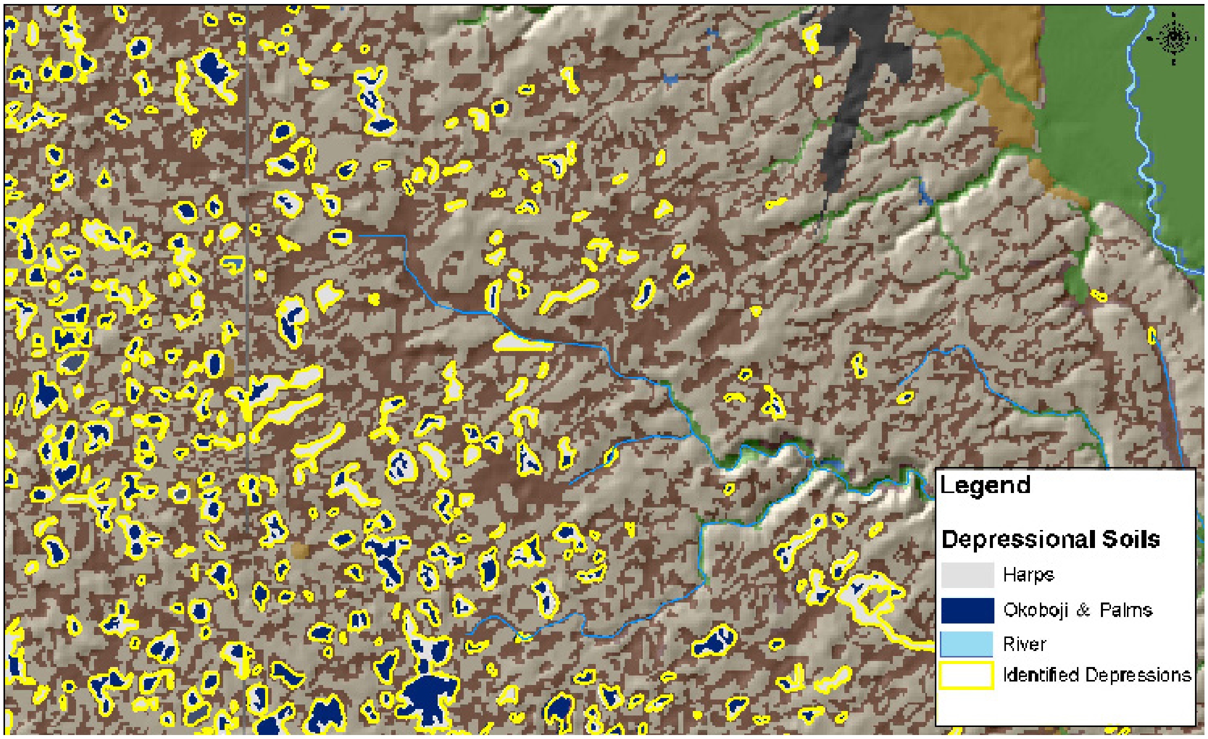

Figure 4. Delineated depressions after identification process.

Some depression delineations were split by county lines. These units were merged together so that the wetland was treated as one unit. The cleaned and verified shapefile was put through a dissolve function. This function brought together adjacent soils that described varying characteristics within a single continuous wetland (Figure 4).

Delineation of capture basins

A digital elevation model (DEM) is a grid format that can be used to consistently approximate flow direction, flow accumulation, and watershed boundaries. Across the entire study area, the best available DEM was the 30 meter national elevation dataset (NED) from the U.S. Geological Survey (USGS-1, 2005). A 30 meter cell size is not ideal for delineating small watersheds. However, if a smaller cell size was available, it would be impractical to compute across the large study area.

Many algorithms have been used to calculate flow direction from an elevation grid. O'Callaghan & Mark (1984) introduced the eight directional model (D8). Each cell is assigned a value representing the direction to the adjacent cell with the steepest downward slope. Subsequent models have attempted to remedy the inherent limitation of forcing flow in one of the available eight cardinal and primary intercardinal directions (i.e. NW,NE, etc.). Costa-Cabral & Burges (1994) tried to improve the algorithm by apportioning flow by an aspect plane with the DEMON model. Although closer to theoretical flow in ideal situations, the DEMON model is problematic and complicated to use (Tarboton, 1997). Tarboton introduced D∞ which apportions flow between the two down slope cells based on how close the flow angle is to the direct angle of those cells. The cell's area then is also proportionally counted with the respective watersheds. Tarboton's algorithm would likely produce more accurate results, but the interface is not yet supported enough for most users to adopt. In addition, D∞ still does not overcome the main limitations of cell size. Flow direction has to be calculated from single elevation values for each cell and flow divides within a cell can not be spatially delineated. Since this study seeks to use methods that are widely reproducible, the simpler D8 model is used.

All cells with flow paths that intersect a certain depression polygon were assigned to be a part of the depression's capture basin. In some cases, multiple flow paths into a wetland polygon yielded multiple watersheds. Watersheds associated with the same wetland were dissolved into a single watershed unit (Figure 5).

The 26 identified wetlands with ratios greater than 1,000 were questionably non-contributing areas. Investigation of these wetlands raised doubt that they were truly isolated depressions. In many cases, these wetlands were likely to soon join the stream network. There was generally a swale type soil adjoining the wetland to a more fluvial 'floodplain' type soil. The high watershed to wetland ratio also indicates a hydrologic load that is likely to easily overflow from the wetland and contribute to stream network flow from normal

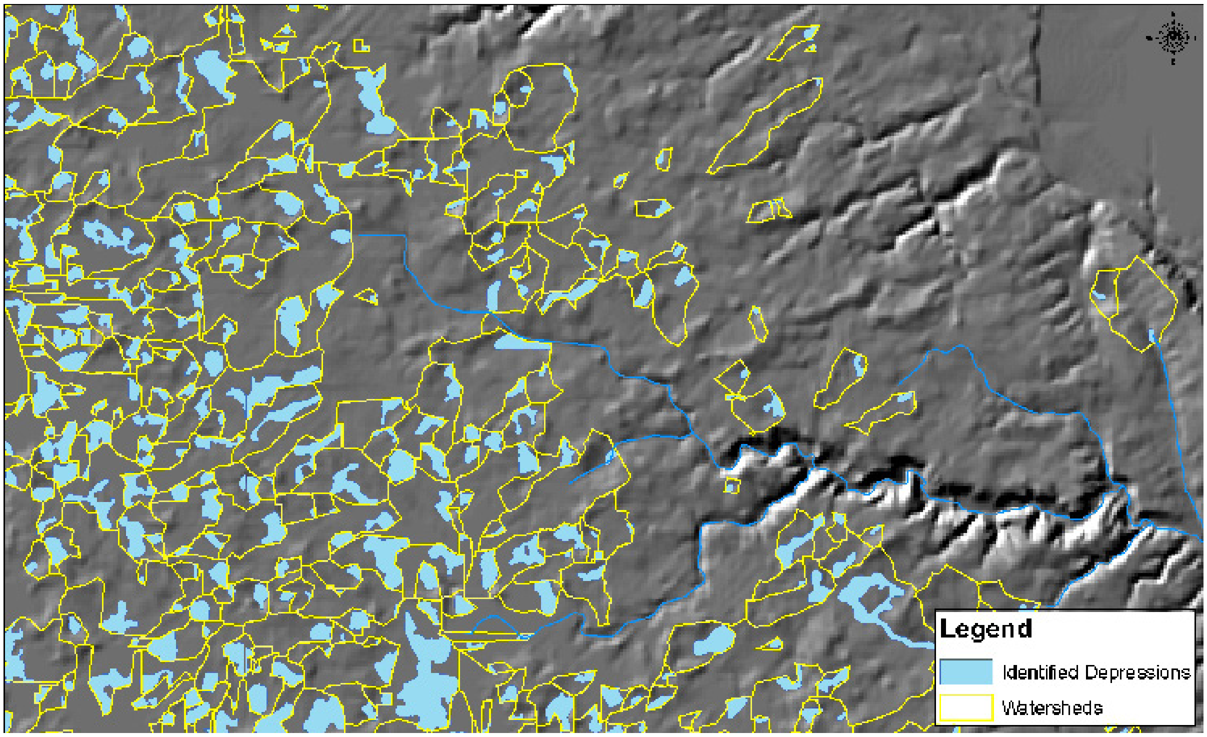

Figure 5. Identified depressional wetlands with delineations of associated watersheds.

rainfall events. For this reason, those 26 sites were removed from the analysis of wetland to watershed size relationships. The range of ratios between 100 and 1,000 still represent a grey area where the hydrologic loading to the wetland would probably often overtop the basin. Investigation of these cases however usually did not show direct swale type connections to the stream network. The total of sites with ratios greater than 100 was only 1.4% of the population.

Identification of trends

This study compared climate and geomorphology trends with the spatial patterns of watershed and wetland parameters. Climate factors are the primary drivers of the inputs and outputs of a depressional wetland's water budget. Since groundwater flow is very slow in the till of this region (Sloan, 1972), groundwater recharge was assumed to be minimal. The main hydrologic inputs to a depressional wetland are direct rainfall and contributions from a wetland's capture basin. Precipitation patterns were assumed to be representative of climate effects on hydrological inputs. The hydrologic output of depressional wetlands is primarily evapotranspiration. Pre-settlement climate information is not readily available. It was necessary to assume that modern climate patterns are representative of pre-settlement climate patterns.

Precipitation data was obtained from the Spatial Climate Analysis Service (SCAS) who used the Precipitation-elevation Regressions on Independent Slopes Model (PRISM) to develop an average precipitation map of the conterminous Unites States (SCAS, 2000). The precipitation map was based on point data from 1961-1990.

The output for a depressional wetland's water budget is naturally dominated by evapotranspiration. Detailed information was not available for evapotranspiration of the same time period. Investigations on the hydrology of depressional wetlands have shown evapotranspiration to fluctuate around the more constant evaporation of a wetland without vegetation (Eisenlohr, 1972). Lake evaporation contours developed by Kohler et al (1959) were assumed to be representative of long term evaporation trends. Kohler calculated the average annual lake evaporation for 1946-1955. The calculated annual average values were then compared with the period of record for each available station with actual evaporation data. The compared stations had data available for 30 to 40 years prior to 1957 and all agreed within 21% of the annual evaporation calculated for 1946-1955.

The major components of a depressional wetland's water budget can be represented by precipitation for the inputs and evaporation for the outputs. The trends of these two climate factors were compared for changes in watershed area, wetland area, and watershed to wetland area ratio.

Geologic zones were derived from state geologic maps and categorizing soil survey map units by parent material. Seven geologic areas were separated as zones of till plains, terminal moraines, and glacial lake beds. The geologic zones were used to represent different landform shapes and geomorphology. It was expected that geologic zones would have the most effect on watershed size.

All three factors were compared visually by trend orientation. For a quantitative analysis, the climate zones and geologic zones were used to summarize site values for a common area. Precipitation and evaporation zones were created between 2 cm isopleths. Because of the strong positive skew of the distribution for all three wetland parameters, the median was used as a measure of central tendency. The median of the zones were compared to each other for each factor to quantitatively analyze for coinciding trends. The median for the intersection of precipitation and evaporation zones was calculated where the intersection area was appropriately larger than a single county area. Care was taken not to compare zones smaller than a county to insure that differences were due to regional trends and not county survey variation. The further division of geologic zones by climate zones was not analyzed because the resulting zone areas would have been smaller than a single county area.

Results

Historical v. Modern Extents of Depressional Wetlands

Within the study area, 86,940 depressional wetlands were identified by categorizing soil survey map units. Visual inspection showed a few sites that were not included by this identification method. The sites that were not included were mapped as part of a soil complex and therefore were not delineated. This author estimates that less than 5% of depressional wetlands were not included.

The number of historical depressional wetlands compared to the number of depressional wetlands identified by the National Wetland Inventory (NWI) demonstrates how drainage systems have modified the hydrology of this landscape (Figure 7). Constraining the NWI to unmodified, palustrine wetlands on the uplands of the Des Moines lobe yielded 22,818 wetlands. This number for wetlands existing today is inflated by the wetland delineations often being smaller than the historical wetland and then divided by roads or

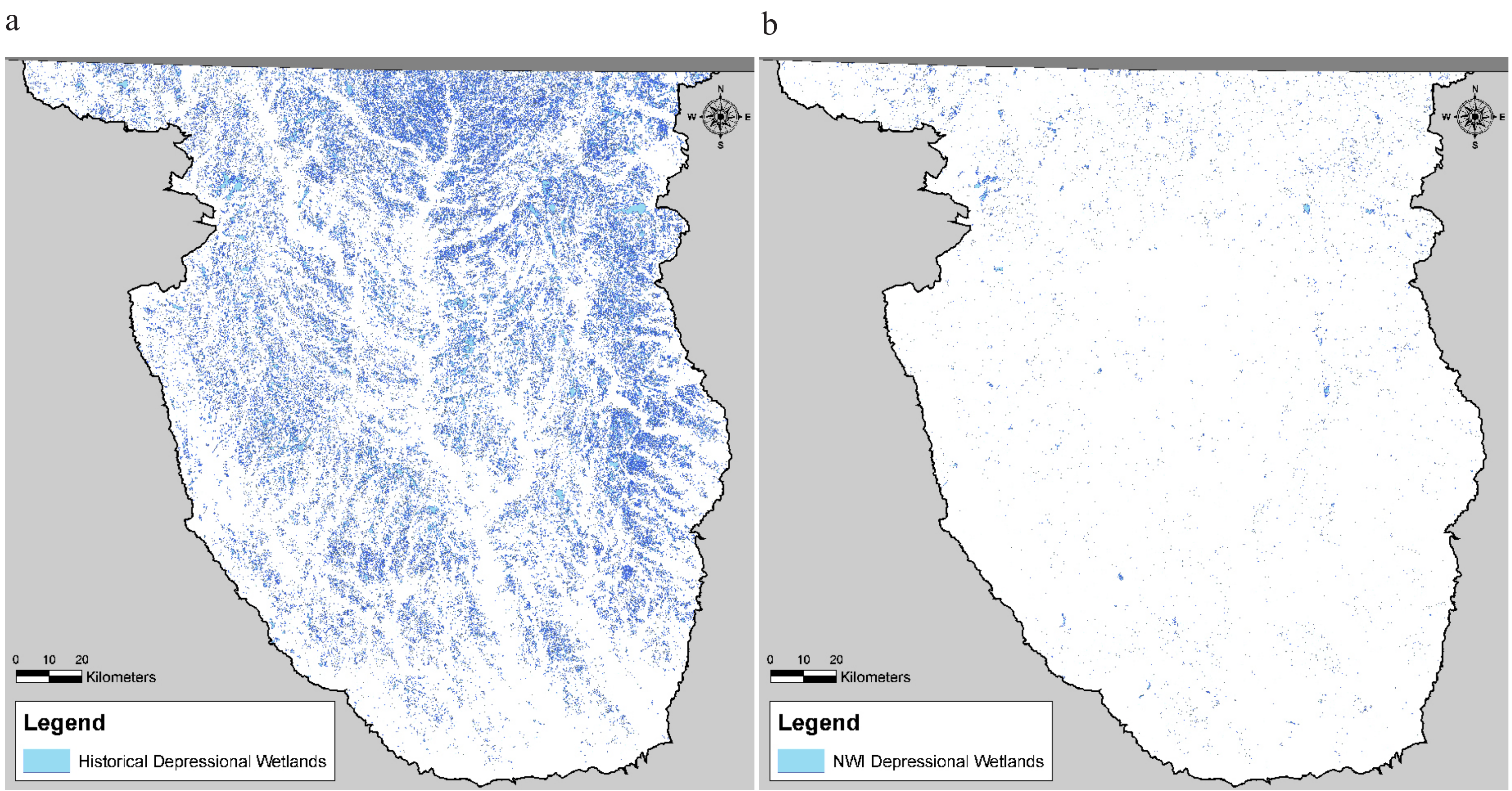

Figure 7. Comparison of depressions existing a) historically and b) today.

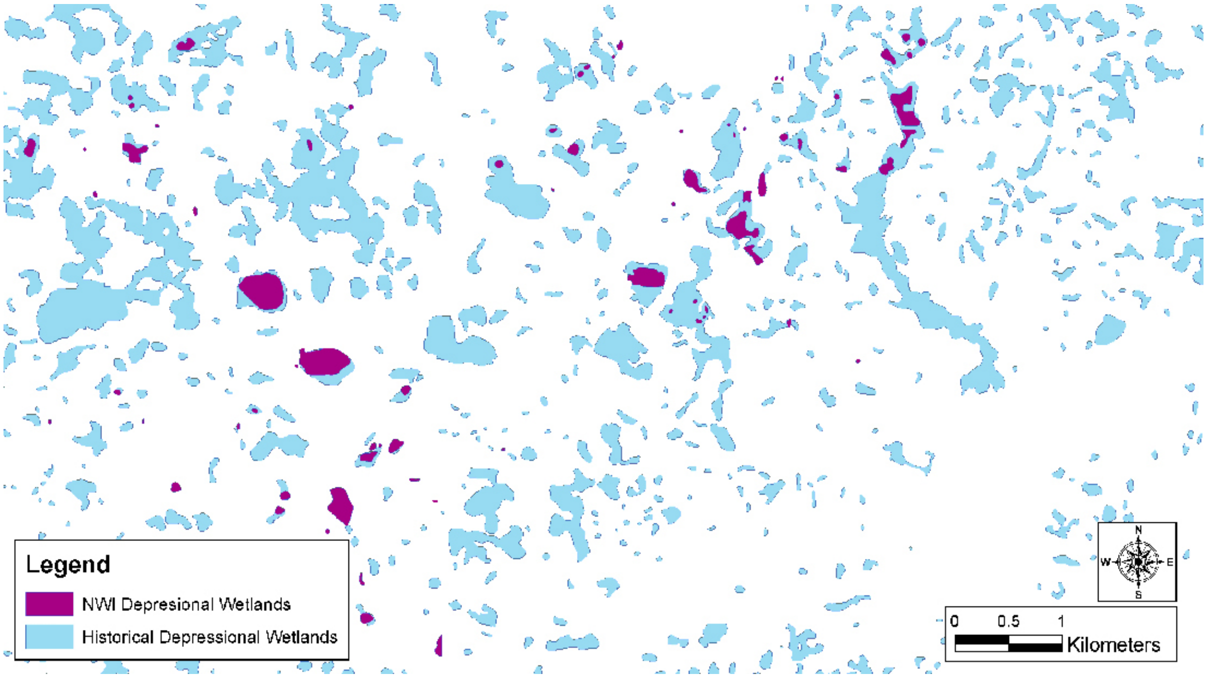

Figure 8. Extent comparison of depressional wetlands existing historically (from soils) and today (NWI).

topography (Figure 8). The total area for all historical depressional wetlands was 1,956,109 acres. The comparable wetlands existing today from the NWI maps have a total area of 29,618 acres. By these estimations of area, 98.5% of historical depressional wetlands have been drained.

Description of Identified Sites

Historical wetland and watershed areas were highly variable across the Des Moines Lobe of Iowa (Table 1). Identified wetland areas ranged from 0.04 to 4,536 acres. Watershed areas ranged from 0.14 to 11,796 acres. Watershed to wetland area ratios varied from 1 to 2,313. In all cases, the distribution of values was strongly positively skewed.

Table 1. Descriptive statistics for sites used in analysis.

	Minimum	**Maximum**	**Median**
Watershed Area (acres)	0.14	11,796.16	14.24
Wetland Area (acres)	0.04	4,535.96	2.00
Ratio	1.00	985.16	4.64

Mapping the central points and color coding them by watershed area, wetland area, and watershed to wetland area ratios shows the large variability and some regional trends. Accepting that some visual differences can be seen between counties, other patterns can be seen within counties and across several counties (Figure 9). Wetland area is the most susceptible to county survey variation. Watershed size is affected when multiple wetlands have been aggregated together in the survey. In those cases, the wetlands' watersheds are combined together and counted as one larger watershed. The watershed to wetland area ratio is the least susceptible to county differences because when wetland area is increased by aggregation, watershed area is also increased. Although the ratio of the internal wetlands is averaged, the result is still a reasonable estimation of watershed to wetland area ratio.

Table 2. Key for color coded points. Legend categories are by quantiles.

Watershed Area	Wetland Area	Ratio	Color Code
0.14 - 2.51	0.04 - 0.88	1.00 - 1.42	
2.52 - 5.17	0.89 - 1.32	1.43 - 2.10	
5.18 - 8.86	1.33 - 1.84	2.11 - 2.80	
8.87 - 14.02	1.85 - 2.45	2.81 - 3.62	
14.03 - 21.11	2.43 - 3.20	3.63 - 4.66	
21.12 - 31.40	3.21 - 4.28	4.67 - 6.13	
31.41 - 47.79	4.29 - 6.08	6.14 - 8.45	
47.80 - 77.74	6.09 - 9.64	8.46 - 12.70	
77.75 - 153.34	9.65 - 19.84	12.71 - 23.24	
153.35 - 11,796.16	19.85 - 4,535.96	23.25 - 985.16	

Trend Analysis

Precipitation increases with a general southeast trend (Figure 10). Evaporation increases with a general southwest trend (Figure 11). The watershed to wetland area ratios visually show a west to east pattern of decreasing ratios to the east. Visual inspection of the patterns does not demonstrate a direct relationship of watershed to wetland area ratios with either precipitation or evaporation, but perhaps an interaction of the two.

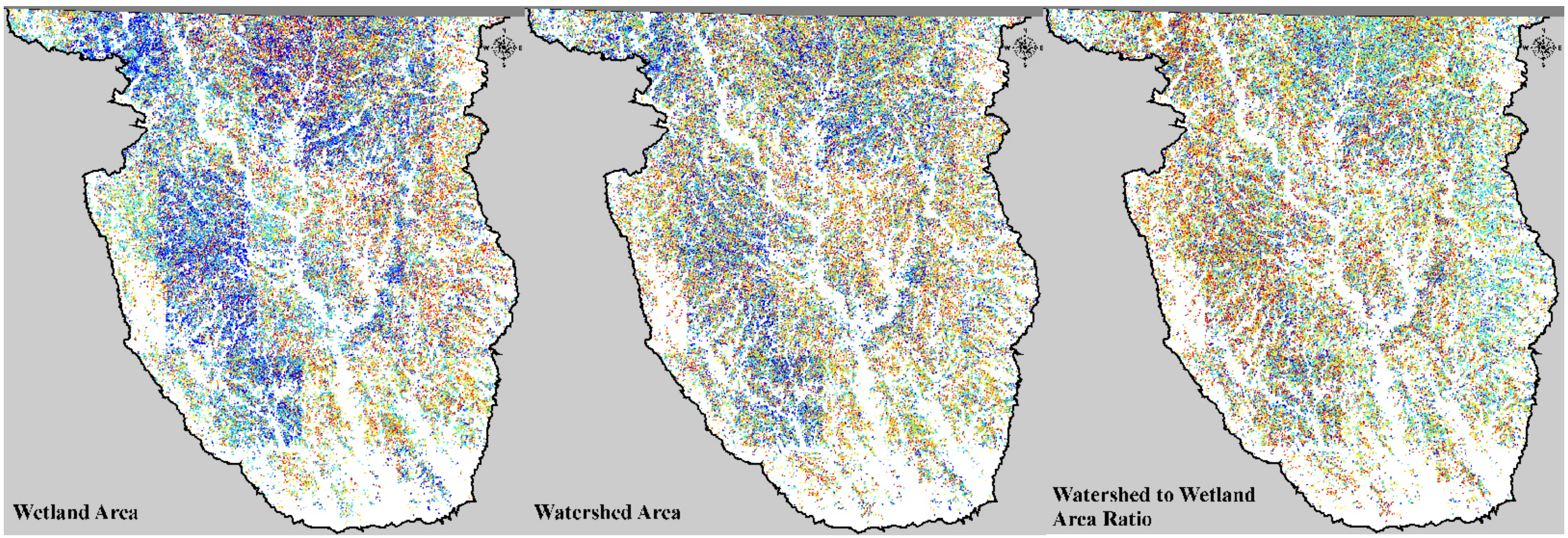

Figure 9. Point maps for wetland area, watershed area, and watershed to wetland area ratio. See Table 2 for color legend.

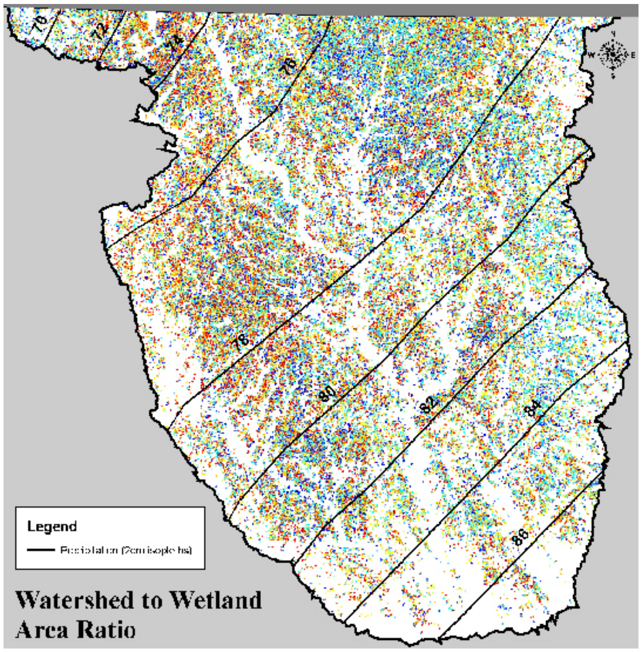

Figure 10. Precipitation trends with watershed to wetland area ratios. Precipitation isopleths based on OCS's PRISM map. See Table 2 for watershed to wetland area ratio point color legend.

Table 3. Median values for zones of precipitation.

Precipitation Zone (cm)	Median Ratio
68-72	4.22
72-74	5.66
74-76	4.96
76-78	4.55
78-80	4.74
80-82	4.45
82-84	4.57
84-86	4.73
86-88	5.32

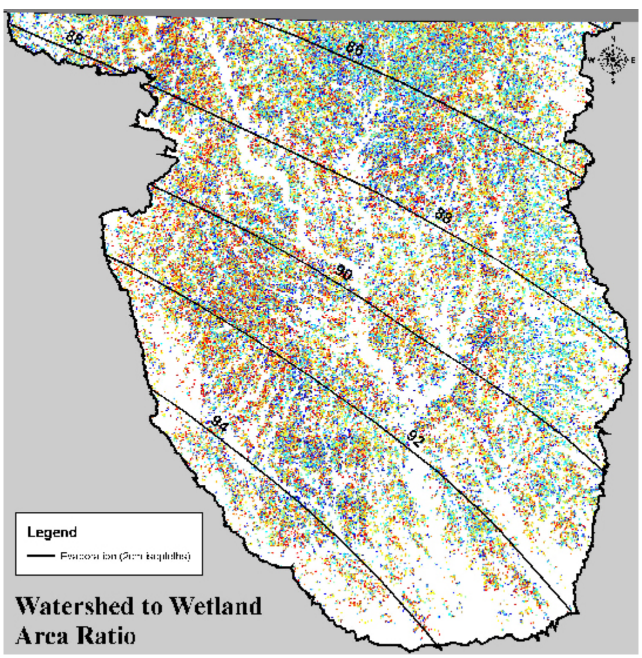

Figure 11. Evaporation trends with watershed to wetland area ratios. Evaporation isopleths based on Kohler's lake evaporation map. See Table 2 for watershed to wetland area ratio point color legend.

Table 4. Median values for zones of evaporation.

Evaporation Zone (cm)	Median Ratio
84-86	4.30
86-88	4.34
88-90	4.75
90-92	5.08
92-94	4.80
94-96	5.40

The median watershed to wetland area ratio of precipitation zones do not clearly reflect a corresponding trend (Table 3). Although precipitation is likely having an effect, another factor is having a more dominant effect on ratios. Evaporation, on the other side of the water budget, has median ratio values for zones following a clearer trend. With the exception of the 90-92 cm evaporation zone, evaporation zone values follow the expected trend of increasing ratios with increasing evaporation (Table 4).

The balance of precipitation and evaporation was analyzed by the intersection of both sets of zones. The medians for intersected zones significantly smaller than a county were not calculated because analysis of those zones increased the possibility of county variation affecting results. The combination of precipitation and evaporation represent effective wetness of the area. The zone with the most precipitation and the least evaporation would have the wettest conditions for producing a wetland.

For most intersected zones, the trend of decreasing watershed to wetland area ratios with wetter conditions holds true (Table 5). The influence of precipitation on watershed to wetland area ratio has a more consistent trend within a constant evaporation range. The correlation between drier conditions and higher ratios is the most clear by comparing values diagonally across the precipitation-evaporation matrix. Drier conditions are represented by less precipitation and more evaporation. There are a few intersection zones that still deviate from the expected pattern. These zones coincide with some morainal areas which could suggest a geomorphic influence. The most recognizable pattern between geologic zones is the change in density of wetlands between zones. As can be expected with the advancement of a stream network, zones with similar hydrologic histories, but are considered to be older show the smallest density of upland wetlands. The sequence of age associated with these geologic zones trend from oldest in the south to youngest in the north.

Table 5. Median watershed to wetland area values for intersected zones of precipitation and evaporation. Cells to the upper right represent drier conditions and cells to the lower left represent wetter conditions.

Precipitation (cm)	Evaporation (cm)					
	84-86	**86-88**	**88-90**	**90-92**	**92-94**	**94-96**
68-72		4.22				
72-74		5.66				
74-76	4.36	4.83	5.28	5.66		
76-78	4.30	3.94	5.07	5.22	5.88	
78-80	4.26	4.30	5.23	5.41	5.00	5.32
80-82		4.21	4.66	4.81	4.13	4.96
82-84		3.82	3.94	4.95	4.85	6.11
84-86			4.41	4.62	4.97	8.09
86-88				5.24	5.51	

Median watershed size is significantly different between geologic zones (Table 6). From this study it is difficult to associate a pattern of causation, but in terms of depressional wetland hydrology it is notable that watershed sizes can be expected to be different between landform regions.

It appears geologic zone also has an influence on watershed to wetland area ratios. Unlike the gradients associated with climate, geologic zones show boundary differences (Figure 12). The two extremes, the West Bemis and the Algona zones, are close to each other in climate conditions (Table 7). They share similar evaporation, but the 2-4 cm less precipitation received by the West Bemis zone does follow the increase in watershed to wetland area ratio. Since the geologic zones span different climates, much of their differences could be attributed to differences in climate. The South Bemis zone which spans almost the full range of the precipitation and evaporation gradients has the middle ratio of all the geologic zones. The extremes could be explained by the fact that these two geologic zones span less of a climate range than the other geologic zones. Even though watershed to wetland area ratios visually show shifts at geologic zone boundaries, the median values do not demonstrate enough of a difference that is unique from climate gradients.

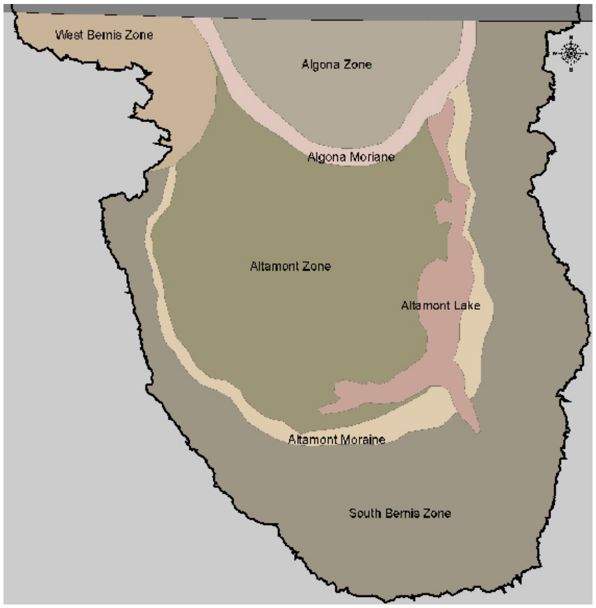

Figure 11. Key to geological zones.

Table 6. Median watershed area for zones of geology. See Figure 11 for zone definitions.

Geological Zones	Median Watershed Area
Algona	13.22
Algona Moraine	11.56
'Altamont Lake'	13.10
Altamont	13.30
Altamont Moraine	17.69
West Bemis	9.46
South Bemis	19.04

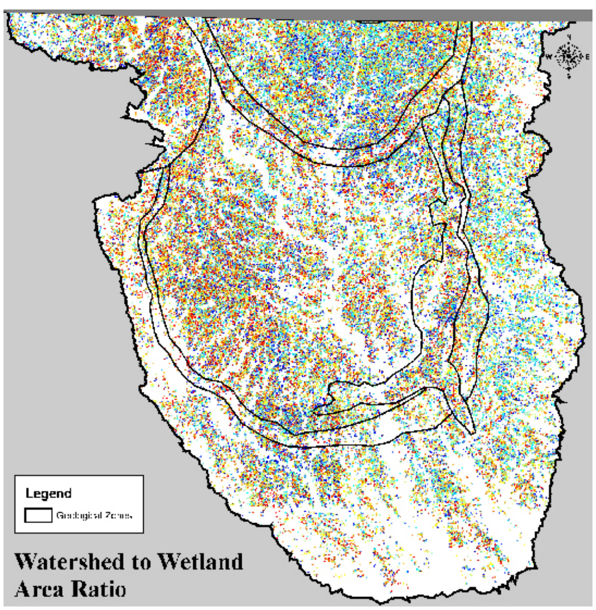

Figure 12. Geology zones with watershed to wetland area ratios. See Table 2 for watershed to wetland area ratio color legend.

Table 7. Median watershed to wetland area ratios for zones of geology. See Figure 11 for zone definitions.

Geological Zones	Median Ratio
West Bemis	5.13
Algona	4.07
Algona Moraine	4.68
Altamont	4.93
'Altamont Lake'	4.54
Altamont Moraine	4.79
South Bemis	4.57

Discussion

Precipitation, as the driving force for the inputs in depressional wetlands' water budget, was expected to be the primary influence on watershed to wetland area ratios. This would cause an expected decrease in watershed to wetland area ratio with increased precipitation. The quantitative analysis of precipitation influence alone did not reflect the expected pattern, which suggests a more dominant factor influencing watershed to wetland area ratios. Evaporation showed a clearer trend of higher watershed to wetland area ratios with more evaporation. Despite the potential of county variation to affect the comparability of smaller zones, the combination of precipitation and evaporation demonstrated the most consistent pattern of higher ratios with drier conditions.

Values from zones that are smaller than counties could be affected by differences in delineation style between county soil surveys. Grouping site values across large areas is expected to rise above measurement biases in county soil surveys by incorporating several counties. Where wetland soils are delineated in smaller units, more wetlands are identified. The resulting watershed for each of those wetlands is smaller because the total watershed that would have been calculated if the wetlands were combined is divided into respective parts for each wetland. Some counties can be seen clearly in the spatial patterns of both wetland size and watershed size. The effect of county differences can be seen clearly because of the anthropogenic straight lines. Patterns caused by non-artificial influences can be seen by transitions that are not corresponding to political boundaries.

Since the methodology of this study is largely based on soil survey information, differences in soil surveys performed on the county level is a possible source of error for perceiving spatial patterns. One way to check this is to visually compare the spatial patterns for correspondence with divisions of concern for explanatory power. Differences between the surveying of counties can be best described by the year the survey was performed. Time differences in when the survey was performed cause variability because soils change over time and surveys have become more detailed. The relative dates of surveys are also an indicator for the likelihood of the surveys to have been done by the same or different surveyors. The greater the span in dates between county surveys the greater likelihood that the survey was done by a different person. The dates for the mapping used in the SSURGO data set was assumed to be the same as the most recently published survey for that county.

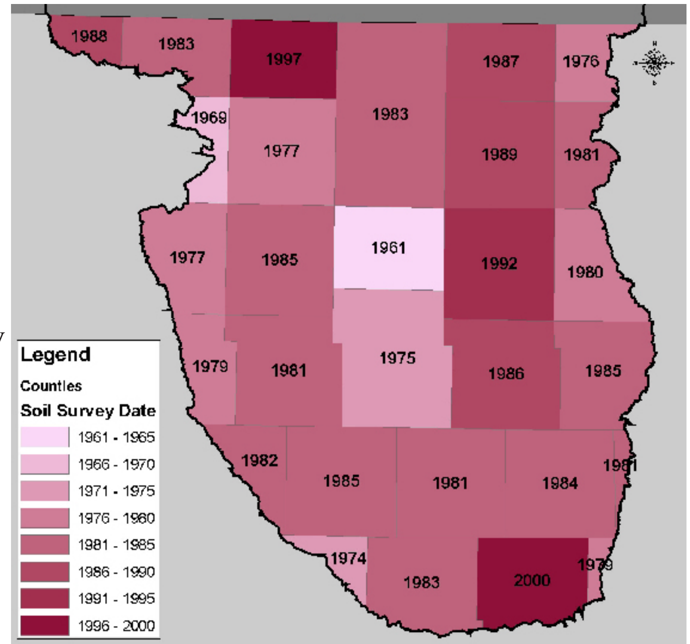

Figure 13. Iowa counties of the Des Moines Lobe displaying pattern of soil survey date.

The dates of soil surveys appear to be fairly random (Figure 13). There are some clusters of two or three counties with similar dates, but they do not follow the general trends identified in this study.

The use of a 30 meter grid for determining flow direction did present some limitations. Watersheds were determined by attributing a cell to a certain wetland's watershed. The watershed boundaries were then drawn in reference to each other for smoothing. This creates the possibility for a cell to be divided into fractions. If only one cell was attributed to a wetland, it is possible for its boundary to be drawn at a minimum area of 576 m^2 (0.14 acres). This is the lower limit of watershed size that can be identified using these methods. The wetland sizes are not affected by grid cell size. The limitation in the watershed delineation is more evident in the lower bound of ratios. While the watershed cells are limited to simple sided geometries, wetland shapes are not. The computer representation of these two components can then have a ratio less than 1. In reality this can not happen, therefore the ratio values were constrained to a lower limit of 1. This is still a reasonable estimate for these watersheds because to produce such a result would require the real dimensions to be close to a ratio of 1.

Conclusions

Soil survey information can be used to identify the extents of historical depressional wetlands. Comparison with comparably mapped wetlands in the National Wetland Inventory confirms earlier observations that large extents of wetlands were drained from this landscape. This method identified that 98.5% of the depressional wetland area has been drained from the Des Moines Lobe of Iowa.

Climate is the dominant influence on the watershed to wetland area ratio of depressional wetlands. Despite the potential of landscape to influence the watershed to wetland area ratio, climate showed a generally smooth correlation. Of the climate components, evaporation shows the strongest effect. This illustrates the dominant role that evaporation has in the hydrology of depressional wetlands and this landscape.

References

Band, L.E. 1986. Topographic partition of watersheds with digital elevation models. *Water Resources Research WRERAO*. 22(1):15-24.

Batt, D.J., M.G. Anderson, C.D. Anderson, and F.D. Caswell. 1989. The use of prairie potholes by North American ducks. *In* Northern prairie wetlands. ed. A.G. van der Valk, p. 204-267. Iowa State University Press. Ames, IA.

Costa-Cabral, M. and S.J. Burges. 1994. Digital elevation model networks (DEMON): A model of flow over hillslopes for computation of contributing and dispersal areas. *Water Resources Research*. 30(6):1681-1692.

Eisenlohr, W.S. et al. 1972. Hydrological investigations of prairie potholes in North Dakota, 1959-68. *U.S. Geological Survey Professional Paper 585-A*. Washington D.C.: U.S. Government Printing Office.

Ellis, J.H. 1938. The soils of Manitoba. *Manitoba Economic Survey Board*. Winnipeg, Manitoba.

Galatowitsch, S.M. and A.G. van der Valk. 1994. Restoring prairie wetlands: An ecological approach. Iowa State University Press. Ames, IA.

Hewes, L. 1951. The northern wet prairie of the United States: Nature, sources of information, and extent. *Annals of the Association of American Geographers*. 41(4):307-323.

Jenny, Hans. 1941. Factors of soil formation: A system of quantitative pedology. McGraw-Hill, 1941. New York, New York.

Jenson, S.K. and J.O. Domingue. 1988. Extracting topographic structure from digital elevation data for geographic information system analysis. *Photogrammetric Engineering and Remote Sensing*. 54(11):1593-1600.

Khan, F.A. and T.E. Fenton. 1994. Saturated zones and soil morphology in a mollisol catena of central Iowa. *Soil Science Society of America Journal*. 58:1457-1464.

Kohler, M.A., T.J. Nordenson, and D.R. Baker. 1959. Evaporation maps for the United States. U.S. Weather Bureau, Washington D.C. Technical Paper No. 37.

Morris, D.G. and R.G. Heerdegen. 1988. Automatically derived catchment boundaries and channel networks and their hydrological applications. *Geomorphology*. 1:131-141.

O'Callaghan, J.F. and D.M. Mark. 1984. The extraction of drainage networks from digital elevation data. *Computer Vision, Graphics and Image Processing*. 28:328-344.

Spatial Climate Analysis Service, Oregon State University, 2000. Annual average precipitation: United States of America. [Online] Available: http://www.ocs.orst.edu/prism/.

Shjeflo, J.B. 1968. Evapotranspiration and the water budget of prairie potholes in North Dakota. *U.S. Geological Survey Professional Paper 585-B*. Washington D.C.: U.S. Government Printing Office.

Sloan, C.E. 1972. Ground-water hydrology of prairie potholes in North Dakota. *U.S. Geological Survey Professional Paper 585-C*. Washington D.C.: U.S. Government Printing Office.

Stanton, G.P. 2001. A comparison of manual and computer-assisted drainage delineation methods for hydrologic-unit map development. p. 1118-1127. *In* Sustaining the Global Farm. Selected papers from the 10th International Soil Conservation Organization Meeting held May 24-29, 1999 at Purdue University and the USDA-ARS National Soil Erosion Research Laboratory. eds. D.E. Stott, R.H. Mohtar and G.C. Steinhardt.

Tarboton, D.G. 1997. A new method for the determination of flow directions and upslope areas in grid digital elevation models. *Water Resources Research*. 33(2):309-319.

U.S. Department of Agriculture, Natural Resources Conservation Service-1, 2005. Soil survey geographic (SSURGO) database. [Online] Available: http://www.ncgc.nrcs.usda.gov/products/datasets/ssurgo/.

U.S. Department of Agriculture, Natural Resources Conservation Service-2, 2005. Official soil series descriptions (OSD). [Online] Available: http://soils.usda.gov/technical/classification/osd/.

U.S. Geological Survey, 2005. National elevation dataset. [Online] Available: http://ned.usgs.gov.

van der Valk, A.G. and C.B. Davis. 1978. The role of seed banks in the vegetation dynamics of prairie glacial marshes. *Ecology*. 59(2):322-335.

Vepraskas, M.J. 1994. Redoximorphic features for identifying aquic conditions. North Carolina Agric. Res. Serv. Technical Bulletin 301. North Carolina State University, Raleigh, North Carolina.

Vepraskas, M.J. and S.P. Faulkner. 2001. Redox chemistry of hydric soils. p. 85-105. *In* J.L. Richardson and M.J. Vepraskas (ed.) Wetland soils: Their genesis, hydrology, landscape and separation into hydric and nonhydric soils. CRC Press, Boca Raton, FL.

CHAPTER 3. DELINEATION OF NON-CONTRIBUTING AREAS OF THE SOUTHERN DES MOINES LOBE USING UPLAND DEPRESSIONAL WETLAND SOILS TO LOCATE HYDROLOGICAL END POINTS

A paper to be submitted to Water Resources Research

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Abstract

Traditional methods of delineating non-contributing areas have been tedious and subject to human interpretation, particularly in areas of low relief. A geographic information system (GIS) method of delineating non-contributing areas would produce consistent results. The decrease in time required to delineate non-contributing areas with a GIS method would make it practical to perform regional scale analysis of non-contributing areas. This study uses upland depressional soils to locate the hydrologic end points of the historically non-contributing areas in the southern Des Moines Lobe. Grid based modeling of flow direction already in use for watershed delineation is used to find the hydrologic end points' watersheds. Those watersheds combined are the region's non-contributing area.

The resulting map showed that 60% of the southern Des Moines Lobe was historically non-contributing. The increase in contribution to annual stream flow from drainage of a previously non-contributing area is a function of the increase in drainage area and climate conditions. For three watersheds on the southern Des Moines Lobe, it was estimated that drainage of the non-contributing area could have approximately doubled the quantity of water flowing in the respective streams. The twelve geologic zones used in this study show a parallel between time and stream network advancement except for areas affected by large quantities of water flowing in a glacial outlet river.

Introduction

Current methods of non-contributing area delineation depend on topographic interpretation. Overland flow direction is determined as perpendicular to elevation contour lines. In high relief areas, drawing drainage divides is easy because the contour lines are close together. Low relief areas are much more difficult because of wider gaps between contour lines. Wider gaps between contour lines combined with human interpretation introduce variability in the definition of drainage divides.

Figurski and Maidment (2001) developed algorithms for use with GIS for delineating non-contributing areas. Their method depended on a digital elevation model (DEM) with a 30 meter cell size, which is the best available resolution for most areas. Their algorithm used elevation 'pits' of a defined depth as end points for delineating non-contributing subwatersheds. The authors felt that a finer resolution elevation model was required for their process to accurately calculate non-contributing areas. Depending on a 30 m cell size to locate hydrologic end points could have been problematic. Depressions in an area such as the southern Des Moines Lobe can often not have enough relief to be distinguishable in the 900 m^2 area defined by a 30 m cell.

Depressional wetlands in non-contributing areas are hydrological end points that serve as common depositories of sediment in closed systems (Walker, 1966; Ruhe, 1969). Specific soil types are formed under the conditions of the alluvial parent material and ponding of water. Maps of these soils can be used to identify the hydrologic end points. The watershed of an upland depression is called a closed basin. The combination of all closed basins is the non-contributing area within a region.

The southern Des Moines Lobe is known for being successfully transformed into an area of high agricultural production by the installation of artificial drainage networks. Tile lines and drainage ditches remove excess water from the historically non-contributing areas. Nearly all of the historical non-contributing area of the southern Des Moines Lobe has been artificially drained. Without artificial drainage the primary outlet for closed basins is evapotranspiration (Shjeflo, 1968). Instead of leaving upland watersheds to the atmosphere, artificial drainage networks provide another route for water to leave closed basins.

There is little record of stream hydrology before artificial drainage was implemented. Identifying the historical non-contributing area is a major part in reconstructing the pre-settlement hydrology because for a given depth of precipitation, the area of a watershed determines the volume input for the watershed's water budget.

Non-contributing areas are not completely isolated, but the description is still justified by the low percent of water volume that reaches a stream from a closed basin. The volume of water that is input to the closed basin has three possible outlets: to the stream network as groundwater, to the stream network by overtopping the closed basins, and to the atmosphere via evapotranspiration. The amount of groundwater recharge from the clay-rich soils of the Des Moines Lobe's non-contributing areas is very limited (Keller et al, 1989; Hayashi et al., 1998). The closed depressions of the southern Des Moines Lobe can also overtop and contribute to stream flow under extremely wet conditions. For the non-contributing area to surficially contribute water to a stream, each closed basin between the raindrop's entry into the watershed and the stream must overtop. Only when the closed basin closest to the stream overtops does water surficially contribute to the stream. Even in this case, only the water that exceeds the closed basins' storage capacity is contributed.

Delineation of the non-contributing area also has geological utility. As a stream network advances into a landscape, a smaller percentage of the area is non-contributing. Therefore the percent non-contributing area is a measure of the advancement of the stream network. The advancement of the stream network is a function of time and hydro-erosional processes. A measure of the advancement of the stream network then can be used comparatively to infer information about the area's hydrological history. If one of the variables affecting the advancement of a stream network is known, then the other can be deduced.

Methods

Description of Study Area

For this study, the southern Des Moines Lobe is defined as the extent of soils associated with the southern region of the Des Moines lobe parent material such as Clarion, Nicollet, Webster, Canisteo, and Okoboji. This region is outlined by the Big Stone moraine in Minnesota to the north and the Bemis moraine extending from the Big Stone moraine to the present day city of Des Moines, IA (Figure 1). The area associated with the Pine City moraine was excluded because of its ambiguous position with the Bemis moraine and absence of the main soil association. Digital soil survey information was not available for Lincoln, Scott, and Steele counties in Minnesota and were not able to be included in this study. The southern Des Moines Lobe is approximately 80,200 km^2 (30,967 mi^2).

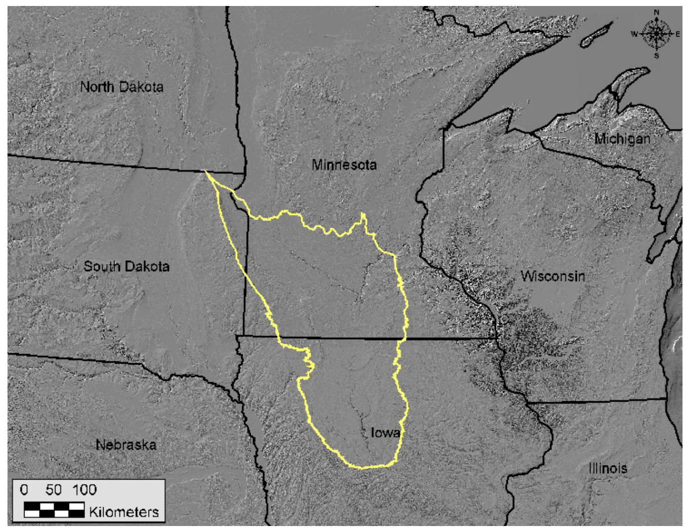

Figure 1. Hillshade map of region with southern Des Moines Lobe highlighted.

Identification of Depressions

To identify historical, depressional wetlands, it is assumed that certain soils can be used to delineate wetlands, even many decades after being drained. Soil survey maps are detailed representations of landscape characteristics. They indicate long-term environmental conditions on a given parent material. Certain soil map units will indicate hydrological end points in the landscape. Not all depressions will be associated with soils classically identified as pothole wetland soils. Understanding of the watershed's morphology is required to identify depressions that have different soil characteristics due to changing environmental conditions, but are still isolated end points for surface flow. The Soil Survey can provide a field-observed data set when concepts of soil morphology are applied.

There is a functional relationship between soil formation factors and soil properties. The factors identified by Jenny (1941) are climate, organisms, relief, parent material, and time. Water is an important force that is included in both climate and relief. The characteristics and spatial patterns of the soils then give us important clues about the hydrology.

Differences in relief result in differences in soil type because the differences in the soil position in relation to relief result in differences in local soil climate. Local variations in topographical position will result in unique soil climates (Ellis, 1938). In the case of depressional wetlands, there would be a very wet soil climate. If the precipitation on a given section of land is 80 cm per year, the soils on the knolls will receive 80 cm minus the amount that runs off. Therefore, the soils on the knolls will have a locally arid soil climate in comparison with regional normal soils. On the other hand, the soils of the depressions will receive 80 cm of precipitation plus the amount of water that runs off from the adjacent higher lands (Figure 2). Therefore, more water will penetrate into or pond on the soils in the lower position.

In the center of many depressions water saturation conditions produce soils that generally exhibit a gleyed horizon and an abundant accumulation of organic matter. These are indicators of long term water saturation coinciding with the existence of a wetland. Accumulation of organic matter can be identified by deep dark layers which occur when water saturation causes anaerobic conditions that suppress decomposition. The anaerobic conditions also cause the reduced state of soil minerals, producing a gleyed chroma (Khan & Fenton, 1994; Vepraskas, 1994; Richards & Vepraskas; 2001). Soils having these

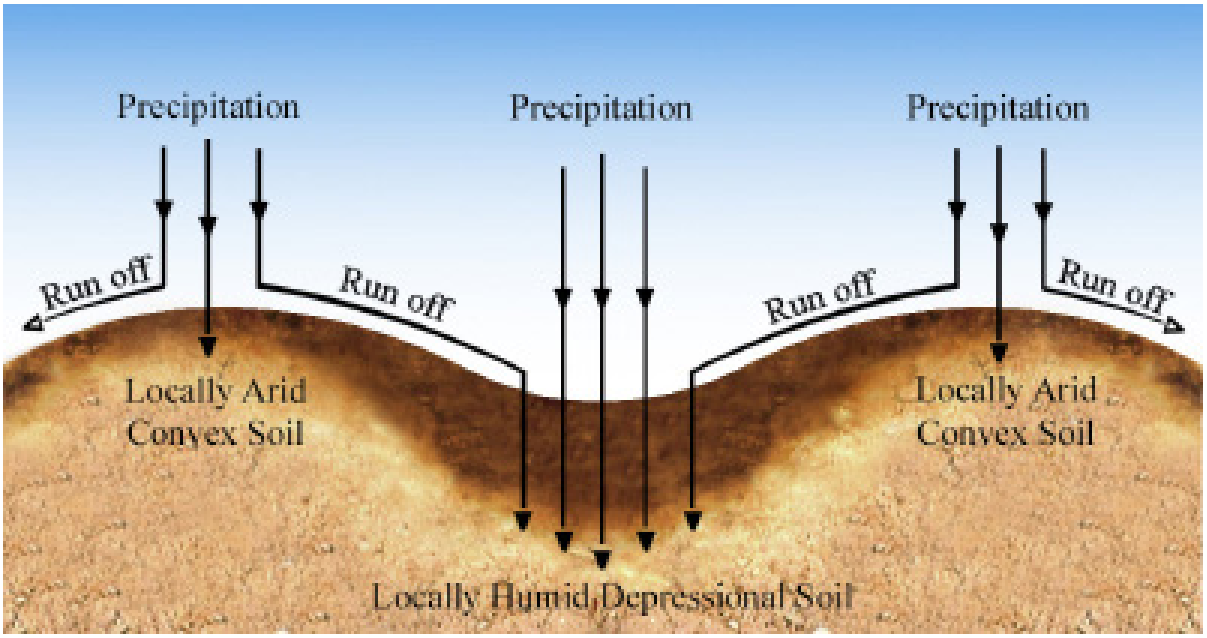

Figure 2. Effect of relief on water penetration of soils (modified from Ellis, 1938).

characteristics indicate long term ponding and the long term average of a wetland's extent. Even if this soil is examined during a dry period or after drainage it will still have many of the properties corresponding to soil formation factors. For this study, it is necessary to assume that the delineations in the soil survey still reflect pre-agricultural conditions.

Digital soil maps were obtained from the Natural Resources Conservation Service's (NRCS) Soil Survey Geographic (SSURGO) Database (USDA-NRCS-1, 2005). The available county soil maps were merged into one coverage and classified for the likelihood of being an upland depressional wetland (Appendix B).

Soil characteristics were interpreted from the Official Soil Series Description available from the NRCS (USDA-NRCS-2, 2005). The first type of soils identified as depressional wetlands were those whose descriptions fully characterized upland, pothole wetland soils such as Okoboji, Knoke, and Palms. These soils are most easily identified in the 'geographic setting' section of the series description. Terms such as depressional and closed depression are the clearest identifiers. If the description only refers to the soil as concave, further investigation is required to distinguish it from a swale soil. The 'drainage and permeability' section can offer important clues about ponding of water. The 'typical pedon' description offers supporting evidence if the profile shows signs of anaerobic conditions, such as an accumulating organic horizon or gleyed chromas. The descriptive information is taken into consideration with examination of examples from the soil survey maps overlaid on an elevation hillshade generated from a digital elevation model (DEM). Taken together, this information provides a reasonable assessment of which soils are long-term, depressional wetlands.

Depressional wetlands are ephemeral in nature and fluctuate considerably in areal extent (van der Valk and Davis, 1978). In many cases, this creates a condition where there is a core wetland soil and a border soil. The border soil shows some evidence of elevated water interaction, but lacks the full degree of signs indicating long-term water saturation. An example of this type of soil in the Des Moines lobe is the Harps soil. It has a general accumulation of calcium carbonate because of the dominant evaporation of sub-surface water, instead of the dominance of water ponding. Evaporation leaves the minerals that were held in solution behind on the soil. The Harps soil is often found surrounding established depressional wetland soils. The Harps soil also sometimes appears to be without a wetland soil in the middle. When the Harps soil occurs alone, it is still indicative of the same topographical conditions. The only difference is that water does not pond in the center for a long enough period to produce the more traditional wetland soil.

Iowa's Soil Properties and Interpretational Database (ISPAID) includes a point data set of soil inclusions that were too small to be delineated. The spot coverage shows many inclusions of soils, such as Okoboji, in areas that should be included as depressional wetlands. The reason for them being spot coverages and not being delineated is because of their small areal size. However, most of the spot locations for depressional soils are accounted for by inclusion within the depressional border soils (Figure 3). The inclusion of both the core depressional soils and the border soils accounts for buffering around larger

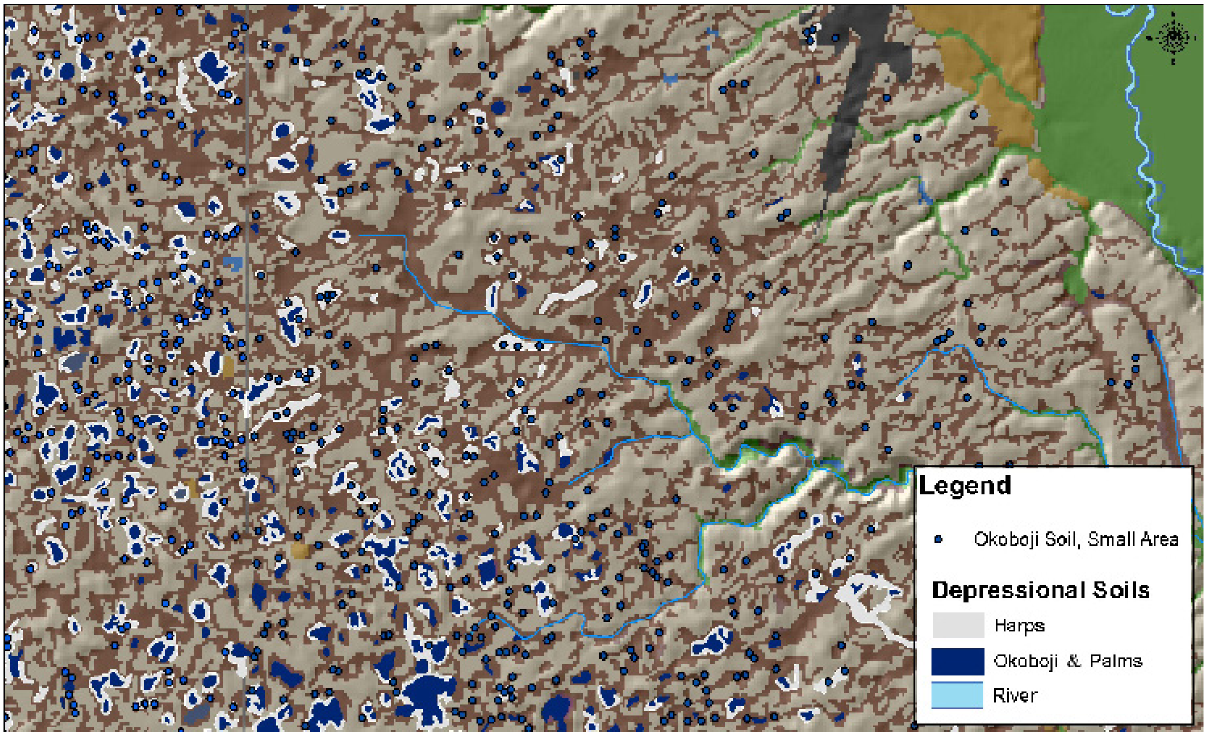

Figure 3. Map of Walnut Creek in Story County, IA. Identified wetland core and border soils are displayed with point locations of inclusions.

depressional complexes, depressions with wetland soils too small for delineation, and depressions that no longer hold enough water to exhibit full wetland soil characteristics.

A database was constructed linking depressional categorization with the SSURGO shapefile using the soil code. All landscape positions that could represent depressions, including those that were classified as water, were selected and exported to a new shapefile. The categorized groups and soil names included as possible depressions are listed in appendix A.

The possible depression map was then visually screened for accuracy. Identified delineations were checked against aerial orthophotos to both insure that man-made structures were not included and that most visually apparent depressional wetlands were included. The majority of removed delineations were water map units that delineated reservoirs, quarries, rivers, riparian wetlands, and large connected lakes. Soil units that were out of place or had an organic parent material were those most commonly removed from floodplain areas. Soils

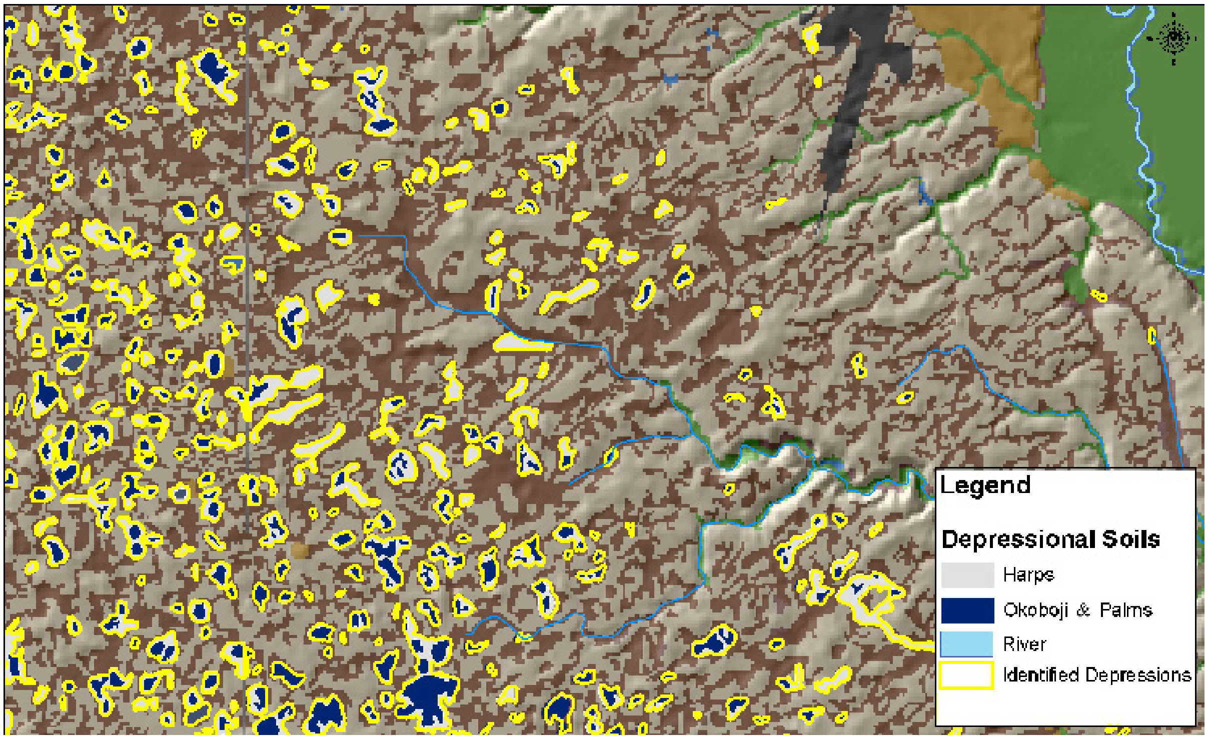

Figure 4. Delineated depressions after identification process.

having descriptions indicating upland formation were sometimes found in floodplain areas. Soils classified with an organic parent material are not defined by a landscape position and were removed when found in floodplain areas.

Some depression delineations were split by county lines. These units were merged together so that the wetland was treated as one unit. The cleaned and verified shapefile was put through a dissolve function. This function brought together adjacent soils that described varying characteristics within a single continuous wetland (Figure 4).

Delineation of Non-Contributing Area

A digital elevation model (DEM) is a grid format that can be used to consistently approximate flow direction, flow accumulation, and watershed boundaries. Across the entire study area, the best available DEM was the 30 meter national elevation dataset (NED) from the U.S. Geological Survey (USGS-1, 2005). A 30 meter cell size is not ideal for delineating small watersheds. However, if a smaller cell size was available, it would be impractical to compute across the large study area.

Many algorithms have been used to calculate flow direction from an elevation grid. O'Callaghan & Mark (1984) introduced the eight directional model (D8). Each cell is assigned a value representing the direction to the adjacent cell with the steepest downward slope. Subsequent models have attempted to remedy the inherent limitation of forcing flow in one of the available eight cardinal and primary intercardinal directions (i.e. NW,NE, etc.). Costa-Cabral & Burges (1994) tried to improve the algorithm by apportioning flow by an aspect plane with the DEMON model. Although closer to theoretical flow in ideal situations, the DEMON model is problematic and complicated to use (Tarboton, 1997). Tarboton introduced D∞ which apportions flow between the two down slope cells based on how close the flow angle is to the direct angle of those cells. The cell's area then is also proportionally counted with the respective watersheds. Tarboton's algorithm would likely produce more accurate results, but the interface is not yet supported enough for most users to adopt. In addition, D∞ still does not overcome the main limitations of cell size. Flow direction has to be calculated from single elevation values for each cell and flow divides within a cell can not be spatially delineated. Since this study seeks to use methods that are widely reproducible, the simpler D8 model is used.

All cells with flow paths that intersect a certain depression polygon were assigned to be a part of the depression's capture basin. In some cases, multiple flow paths into a wetland polygon yielded multiple watersheds. Watersheds associated with the same wetland were dissolved into a single watershed unit (Figure 5). Together, the depression capture basins comprise the non-contributing area. The non-contributing area was delineated by dissolving the capture basin boundaries.

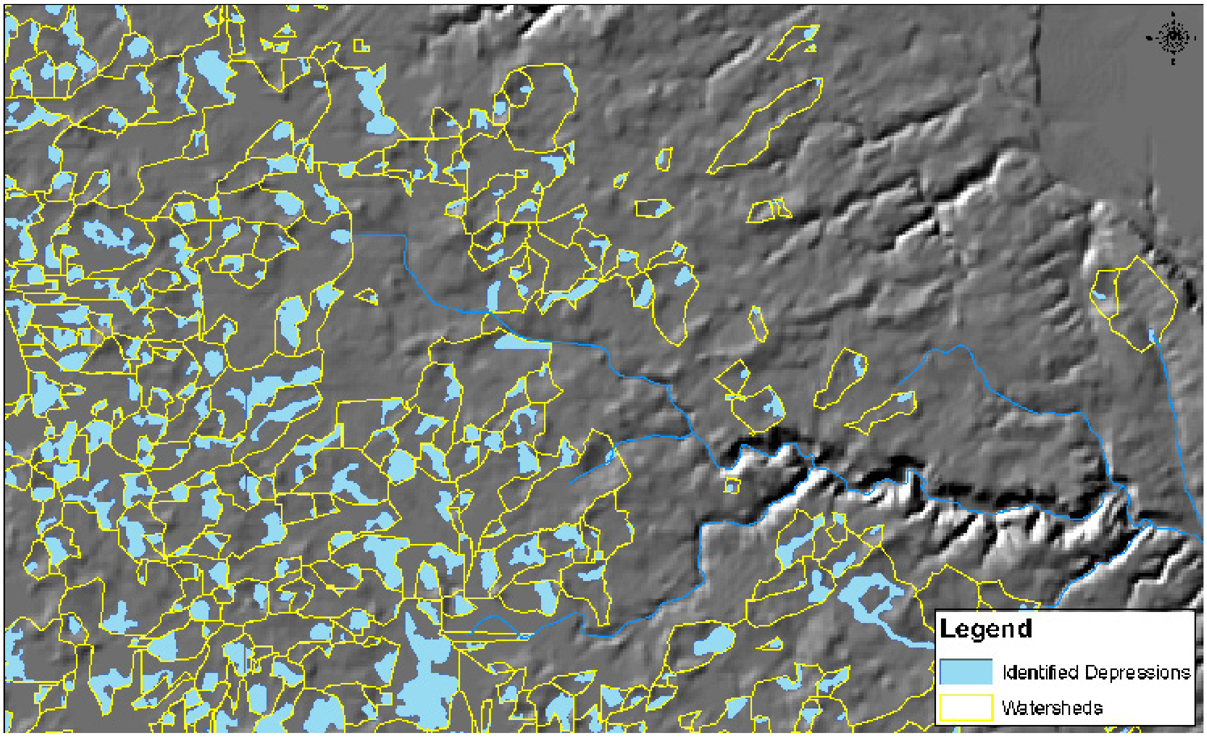

Figure 5. Identified depressional wetlands with delineations of associated watersheds.

Modern Stream Implications

Three gauged watersheds of different size but similar percent non-contributing area were used to illustrate the quantity of water that can be added to stream flow when a drainage network connects all of the pre-settlement non-contributing area. It has been found that water yield calculated for small gauged watersheds are good estimators for water yield in smaller upland watersheds (Portela and Quintela, 2002). Calculating water yield and interpolating across the region estimates the volume of water delivered by an area if it was connected to the stream network. Average 1990s' annual water yield was calculated for regional stream gauges with complete 1990s' records and a total watershed area of less than 2,500 km^2. The point values of those gauges were then used to interpolate a continuous grid across the study area. The water yield values for each cell in the non-contributing area were summed and multiplied by cell area to estimate the annual volume of water coming from the area.

Geological Implications

The study area was divided into twelve geologic zones. The zones were based on formation environment and age. The divisions of formation environments were known terminal moraines, stagnation moraines, ground moraines, and glacial lakes. Percent non-contributing area was calculated for each geologic zone based on the non-contributing area delineation produced in this research. The zones were then compared by age and geologic events that affect the advancement of the stream network.

Results

Map of Region's Non-Contributing Area

The map produced by aggregating the depressions' watersheds identifies 47,900 km^2 of non-contributing area (Figure 6). That is 60% of the study area. Different areas of the landscape can be seen to have more advanced stream networks. The Minnesota River and Des Moines River, which are descendants of large glacial outflows, are primary stems from which the stream network extends. The stream network is also advanced on the regionally steep sides of the Coteau Des Prairies. The Coteau Des Prairies is a low plateau underlain by a ridge of resistant bedrock on the northwestern edge of the study area (Ojakangas and Matsch, 1982).

Potential Annual Contribution of Flow from Drained Areas

The quantity of water that is contributed from an area is variable with climate. In general, areas with more precipitation will yield a greater volume of water per area drained. Therefore the distribution of non-contributing area in a watershed with respect to climate determines the impact on stream flow quantity when the non-contributing area becomes drained. Three gauged watersheds were chosen on the Des Moines Lobe to estimate the potential annual water volume from drained non-contributing areas for their individual

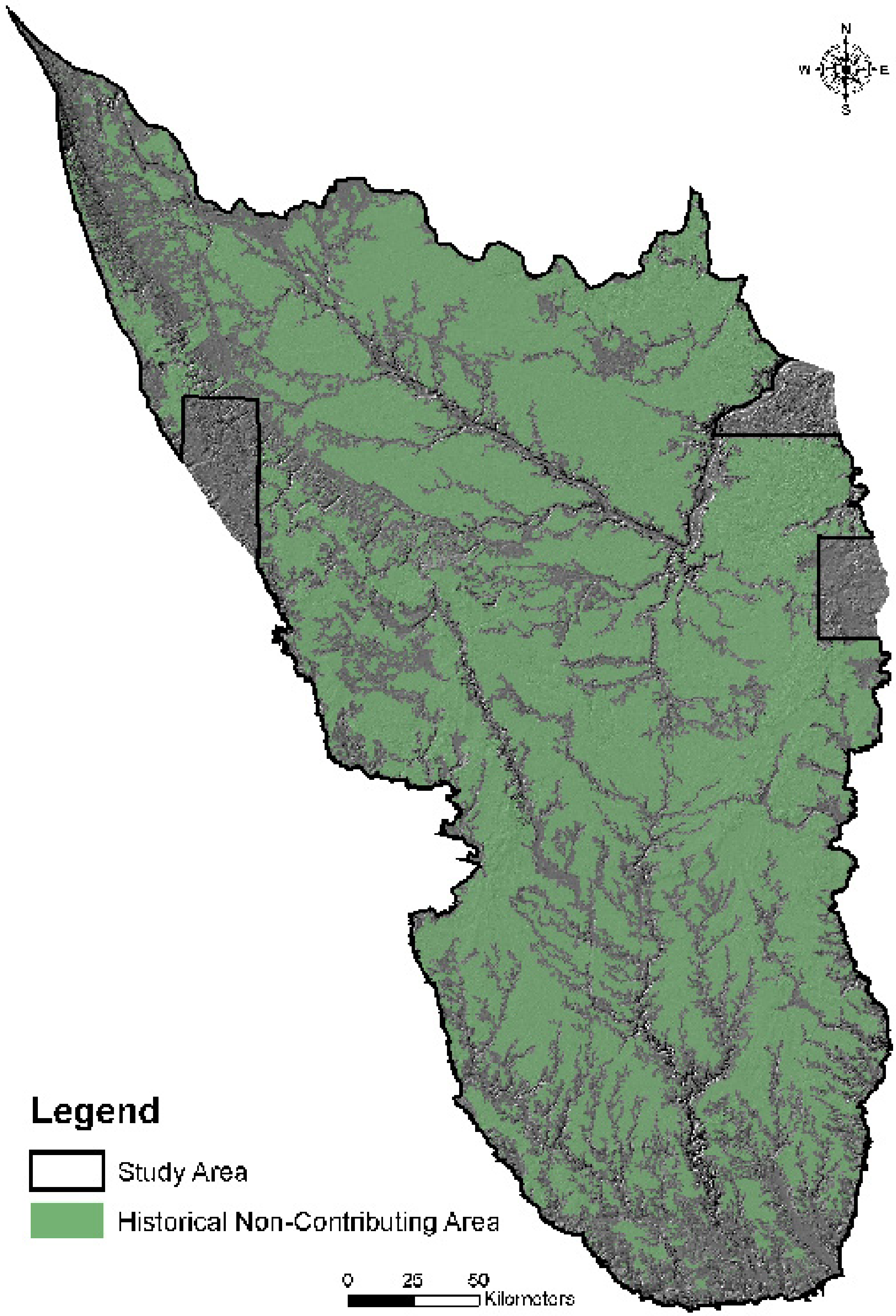

Figure 6. Identified non-contributing area of the southern Des Moines Lobe with elevation hillshade background.

conditions (Figure 7). Each watershed covers a different range of climate conditions. The three watersheds range from 44-64% non-contributing area.

Precipitation in the study area decreases from the southeast to the northwest. The gauges for the Iowa River at Marshalltown and the South Skunk River at Colfax have the higher average water yields. The Des Moines River watershed, which extends into the drier southwestern Minnesota area, has the lower average water yield (Table 1).

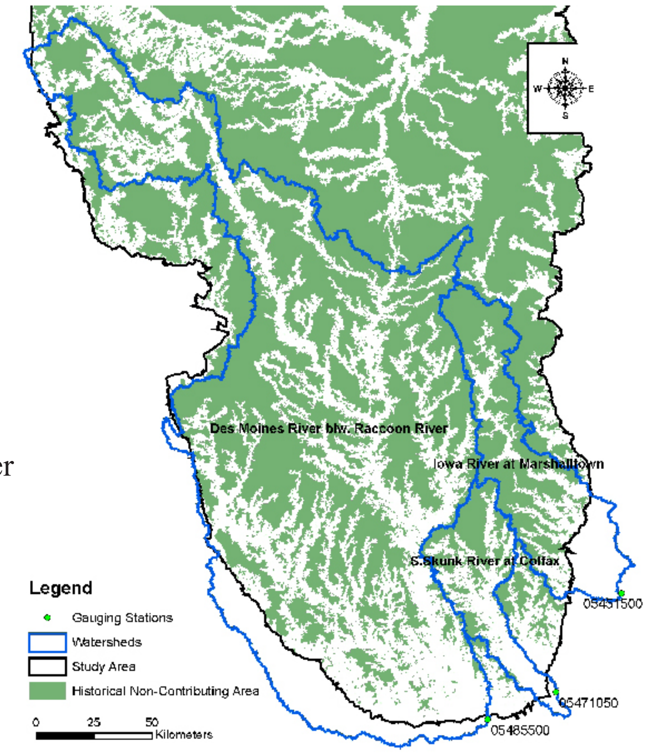

Figure 7. Watersheds used for example of flow added by artificial drainage of non-contributing area.

Table 1. Description values for the three watersheds used in comparison.

	Des Moines River	Iowa River	S. Skunk River
Total Watershed Area (km^2)	25,586	3,968	2,080
1990's Average Annual Flow (m^3)	7.27 x 10^9	1.29 x 10^9	0.66 x 10^9
1990's Average Water Yield (m/yr)	0.28	0.32	0.32

With the assumption that tile networks yield approximately the same volume of water as a natural stream network, the volume of water contributed by draining all of the non-contributing area was estimated by the interpolated water yield grid (Figure 8). For verification, the same method was used to estimate the annual average 1990s' total flow and compared with the observed flow. The water yield grid calculation underestimated the Des Moines River by 10%, the Iowa River by 14%, and overestimated the South Skunk River by 0.3%.

The estimated volume of water from the drainage of all non-contributing areas was then compared with the average observed 1990s' total annual flow (Table 2). The percent contribution from pre-settlement, non-contributing areas was primarily a function of the percent non-contributing area. The percent of flow from these areas varied from the percent non-contributing area because of differences in climate. Changes in climate conditions either decrease or increase the weight of an area with respect to the whole watershed's discharge. If the non-contributing area receives more precipitation than the rest of the watershed, then that area will have a greater per area affect on the total flow of the watershed and vice versa.

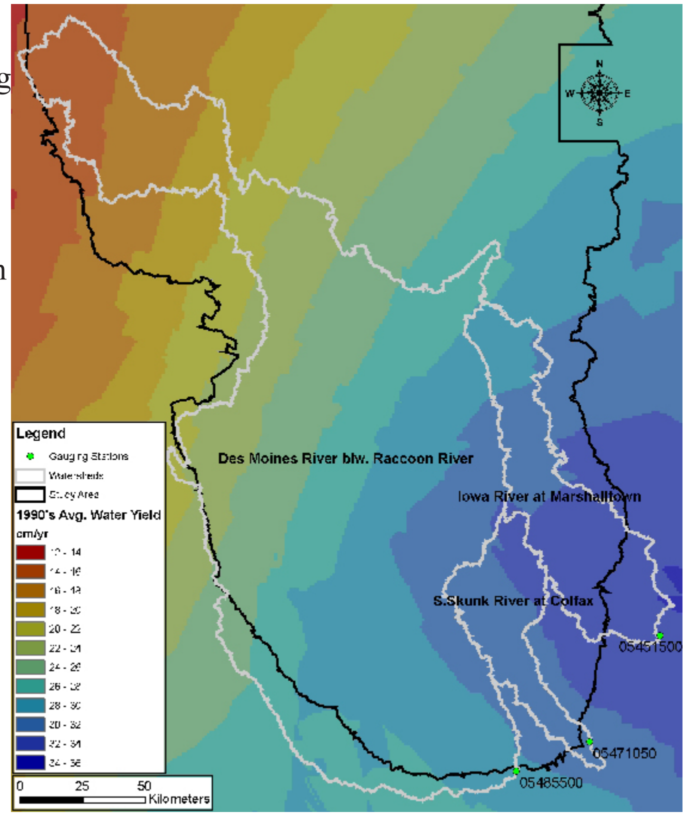

Figure 8. 1990s' average annual water yield interpolated grid with watershed boundaries.

Table 2. Variance of water yield effect on the efficacy of drained areas influence on annual stream discharge

	Des Moines River	Iowa River	S. Skunk River
Non-Contributing Area (km^2)	13,305	2,540	915
% Non-Contributing	52	64	44
Drainage Addition (m^3)	3.36 x 10^9	0.69 x 10^9	0.293 x 10^9
% of 1990's Average Annual Flow	46	54	44

The Des Moines River was estimated to have 46% of its average 1990s' flow contributed from non-contributing areas. The estimated percent of 1990s' flow from the drained non-contributing area of the South Skunk River was coincidently the same as the percent non-contributing area at 44%. Although the overall watershed water yield for the South Skunk River and the Iowa River are similar, the Iowa River has non-contributing area in a drier part of the state. The lower water yield in the upper part of the Iowa River watershed reduces the efficacy of the drained non-contributing area in adding flow to the Iowa River. The percent of the Iowa River watershed that was historically non-contributing was the highest of the three compared watersheds. The resulting estimation of percent of contribution to flow from drained non-contributing area was only 54%, even though the percent non-contributing area was 64%.

Stream Network Advancement in Geologic Zones

The extents of non-contributing areas coincide with geologic zones because of the effect of time and geologic events. The area understood to be the oldest surface is between

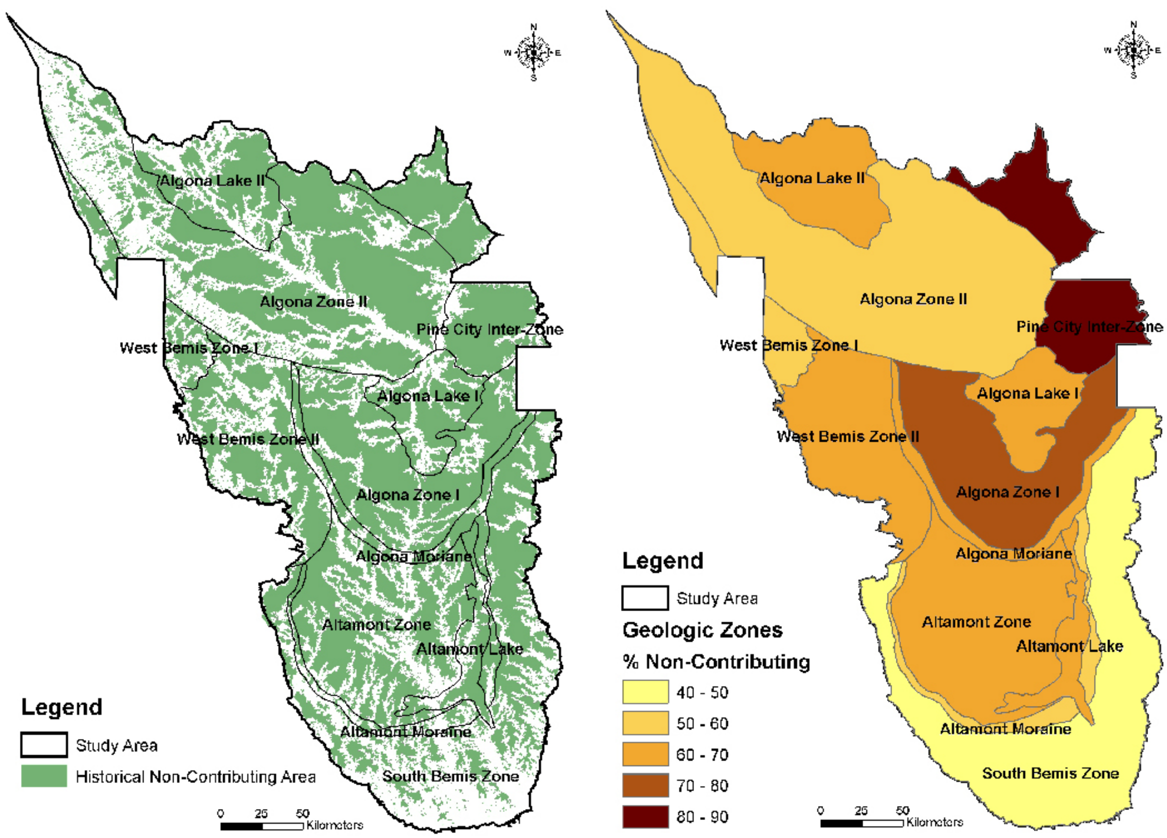

Figure 9. Non-contributing area relationship with geological zones.

the southern most reach of the Bemis moraine and the Altamont moraine. The age of this area is reflected in the low percentage of non-contributing area (Figure 9). The age of the geologic zones are generally understood to be sequentially younger to the north due to their juxtaposition. The sequence of the south Bemis zone, Altamont zone, and Algona zone have a percent non-contributing area corresponding to their relative age.

The percentage of non-contributing area does not always correspond to the relative age of the landscape. The 'Algona Lake' I, 'Algona Lake' II, and Algona II zones have a low percent non-contributing area compared to the presumably older zones to the south. The stream network in the Minnesota River watershed has advanced more rapidly because of the high flows of Glacial River Warren. Glacial River Warren created the valley that the Minnesota River now occupies. It was an outlet river for Lake Agassiz from the Big Stone moraine (Ojakangas and Matsch, 1982). By the graded river concept, the tributary streams in the Algona plain adjusted their morphology with respect to Glacial River Warren. As Glacial River Warren down-cut, the tributary streams eroded headward faster to balance the streams' flow slope with Glacial River Warren's elevation.

Discussion

Modern Streams

The added volume of water in the stream network has affected the modern morphology of streams. Significant changes in the quantity of water being transported in a surface waterway will affect the balance of stream bank erosion. A stream's tendency for channel erosion or sediment deposition is controlled by factors related to the water's ability to transport materials. Water has a propensity to carry with it a critical amount of sediment based on the available energy. Any change in the controlling factors will cause the erosive ability to compensate appropriately (Mackin, 1948). Increasing factors such as velocity or volume will increase the water's tendency to erode. Rivers with increased water loads will have to adjust their shape for the greater water quantities. By the concept of a graded river, an increase in the quantity of water capable of transporting sediment would cause the stream to decrease the flow slope by down-cutting. The steep banks that can be seen on many of Iowa's rivers today may be products of the shift in hydrology caused by artificial drainage.

Interpreting Geologic History from Stream Network Advancement

In most geologic zones, the extent of the stream network agrees with the understood geologic history of the area. The effect of time is demonstrated by the decrease of stream network advancement in the increasingly younger landscapes from the Bemis zone to the Algona zone. The effect of hydrology on graded rivers is demonstrated by the greater level of stream network advancement in zones that had tributaries connected to Glacial River Warren.

The Pine City Inter-Zone has the highest percent non-contributing area. It is characterized by stagnation moraine features. The high percent of non-contributing area despite Glacial River Warren having flowed through it may suggest a formation time line with respect to the other glaciated areas. It could indicate that glacier ice remained there after the main glacier had retreated above the Big Stone moraine and after Glacial River Warren's flow was reduced.

Limitations of Findings

The primary source of error in the delineation of the non-contributing area using this method is the correct identification of hydrologic end points. Soils identified as possible depressions were not always delineations of the intended type of hydrologic end point. Visual screening for delineations of floodplain depressions and man-made structures was crucial. Another challenge to the correct identification of hydrologic end points was the gradient between truly isolated watersheds, watersheds that sometimes connect, and watersheds that freely flow to the stream network. Some judgment was required for which depressions were primarily isolated from the stream network. Depressions that were adjacent to soils formed in alluvium deposited by higher water flows were considered to regularly overflow to the stream network.

Errors in watershed delineation had little or no effect because of the neighbor relationship with other closed basins. The exact boundary of a closed basin was inconsequential after neighboring watersheds where merged together. Any error in watershed delineation would only appear on the outside border of the non-contributing area.

Some non-contributing area was left out because the soil representing the hydrological end point was too small to be delineated on the soil map and was not located inside one of the identified depressional soils. These areas do not have a significant impact on the final results because they would have only been not included when they occurred on the fringe between non-contributing and contributing areas. The size of the soil inclusions also indicates that their respective watershed is not a large area.

Conclusions

Aggregating the watersheds of hydrologic end points identified by depressional wetland soils produced a logical map of the southern Des Moines Lobe historical non-contributing area. This map shows 60% of the southern Des Moines is naturally non-contributing area.

For three watersheds on the southern Des Moines Lobe, the potential percent contribution to annual flow from drained non-contributing areas ranged within 10 of the percent non-contributing area depending on the distribution of climate conditions. In all of these watersheds, it was shown that artificial drainage of the whole non-contributing area has the potential to double the quantity of water flowing in the respective streams.

The twelve geologic zones used in this study show a parallel between time and stream network advancement except for areas affected by large quantities of water flowing in a glacial outlet river. The large quantity of flow caused a faster rate of erosion to the point that areas in the Minnesota River watershed have a more advanced stream network than some older landscapes.

References

Costa-Cabral, M. and S.J. Burges. 1994. Digital elevation model networks (DEMON): A model of flow over hillslopes for computation of contributing and dispersal areas. *Water Resources Research*. 30(6):1681-1692.

Ellis, J.H. 1938. The soils of Manitoba. *Manitoba Economic Survey Board*. Winnipeg, Manitoba.

Figurski, M.J. and D.R. Maidment. 2001. GIS algorithms for large watersheds with non-contributing areas. CRWR Online Report 2001-7. [Online] Available: http://www.crwr.utexas.edu/gis/gishydro02/Library/Figurski/rpt02-1.htm.

Keller, C.K., G. van der Kamp, and J.A. Cherry. 1989. Multiscale study of the permeability of a thick clayey till. *Water Resources Research*. 25:2299-2317.

Khan, F.A. and T.E. Fenton. 1994. Saturated zones and soil morphology in a mollisol catena of central Iowa. *Soil Science Society of America Journal*. 58:1457-1464.

Jenny, Hans. 1941. Factors of Soil Formation: A System of Quantitative Pedology. McGraw-Hill, New York, NY.

Mackin, J.H. 1948. Concept of the graded river. *Geological Society of America Bulletin.* 59:463-512.

O'Callaghan, J.F. and D.M. Mark. 1984. The extraction of drainage networks from digital elevation data. *Computer Vision, Graphics and Image Processing*. 28:328-344.

Ojakangas, R.W. and C.L. Matsch. 1982. Minnesota's geology. University of Minnesota Press, Minneapolis, MN.

Portela, M.M. and A.Quintela. 2002. Assessment of the streamflow characteristics under unavailability of discharge data: The mean annual flow depth over the watershed as a regionalization parameter: The Portuguese case. *EGS XXVII General Assembly, Nice, April 21-26, 2002*. abstract #1163.

Ruhe, R.V. 1969. Quaternary landscapes in Iowa. Iowa State University Press, Ames, IA.

Shjeflo, J.B. 1968. Evapotranspiration and the water budget of prairie potholes in North Dakota. *U.S. Geological Survey Professional Paper 585-B*. Washington D.C.: U.S. Government Printing Office.

Stanton, G.P. 2001. A comparison of manual and computer-assisted drainage delineation methods for hydrologic-unit map development. p. 1118-1127. *In* D.E. Stott, R.H. Mohtar and G.C. Steinhardt, eds., Sustaining the global farm. Selected papers from the 10th International Soil Conservation Organization Meeting held May 24-29, 1999 at Purdue University and the USDA-ARS National Soil Erosion Research Laboratory.

Tarboton, D.G. 1997. A new method for the determination of flow directions and upslope areas in grid digital elevation models. *Water Resources Research*, 33(2):309-319.

U.S. Department of Agriculture, Natural Resources Conservation Service, 2005-1, 2005. Soil Survey Geographic (SSURGO) Database. [Online] Available: http://www.ncgc.nrcs.usda.gov/products/datasets/ssurgo/.

U.S. Department of Agriculture, Natural Resources Conservation Service-2, 2005. Official Soil Series Descriptions (OSD). [Online] Available: http://soils.usda.gov/technical/classification/osd/.

U.S. Geological Survey, 2005. National Elevation Dataset. [Online] Available: http://ned.usgs.gov.

Walker, P.H. 1966. Postglacial environments in relation to landscape and soils on the cary drift, Iowa. Iowa Agricultural Home Economics Experiment Station Resource Bulletin. 549: 838-875.

Hayashi, M., G. van der Kamp, and D.L. Rudolph. 1998. Water and solute transfer between a prairie wetland and adjacent uplands, 1. Water balance. *Journal of Hydrology*. 207(1):42-55.

van der Valk, A.G. and C.B. Davis. 1978. The role of seed banks in the vegetation dynamics of prairie glacial marshes. *Ecology*. 59(2)322-335.

Vepraskas, M.J. 1994. Redoximorphic features for identifying aquic conditions. North Carolina Agric. Res. Serv. Technical Bulletin 301. North Carolina State University, Raleigh, North Carolina.

Vepraskas, M.J. and S.P. Faulkner. 2001. Redox chemistry of hydric soils. p. 85-105. *In* J.L. Richardson and M.J. Vepraskas (ed.) Wetland soils: Their genesis, hydrology, landscape and separation into hydric and nonhydric soils. CRC Press, Boca Raton, FL.

GENERAL CONCLUSIONS

An old maxim from Confucius is "study the past if you would define the future." We know relatively little about the history of the southern Des Moines Lobe before European settlement. There are some written accounts from early pioneers of vast areas of swamps and the ability to cross streams with horses and wagons. For better or for worse, today's landscape is not the same as it was described by those pioneers. Areas that they considered waste land are now among the most agriculturally productive areas in the world. Long gone are the glaciers that shaped the land and deposited the material we depend on for the production of our food and the management of our water. The hydrology that drove diverse vegetation dynamics and supported large populations of waterfowl has been changed. Because of bridges, crossing rivers is not a major concern, but it is hard to imagine wagons safely managing the steep river banks of many streams in Iowa today.

It is clear that dramatic changes have occurred in the southern Des Lobe in the past 150 years. Future management of this landscape towards our quality of life goals would be served by better understanding the history of the landscape. The history provides information about what is there, how it functions, and the impacts of past changes.

Any geologist, soil scientist, or anthropologist will tell you that the best way to learn something about the past is to dig. Because of the long lasting effect of the soil formation factors identified by Jenny (1941), the soil is a record of Quaternary history. That record can be used to reconstruct many of a landscape's historical characteristics. However, soil formation is ongoing. Modern changes in soil climate, erosion, and deposition are modifying soils. The anthropogenic changes in soil formation factors cause a faster rate in the change of soil properties than most of the conditions that produced the pre-settlement properties of soils. For that reason, the use of soils is an eroding opportunity to reconstruct historical characteristics of a landscape.

Results in the present study show that interpretation and management of soil survey data can be used to efficiently create Quaternary geology maps, reconstruct the extent and hydrology of historical depressional wetlands, and reconstruct regional historic hydrology of watersheds with non-contributing areas. Quaternary geology maps derived from the categorized soil map units added resolution and showed close agreement with currently available Quaternary geology maps. This study found the extent and respective hydrologic load of depressional wetlands that have been drained for more than 50 years. Those interested in restoring depressional wetlands can use this method to estimate the hydrology that affects vegetation dynamics in the wetlands to be restored. GIS methods were used to produce a consistent and reproducible delineation of the region's non-contributing area. An estimation of water yield enabled the assessment of how artificial drainage practices have impacted the quantity of water flowing in the stream network.

In each of the chapters of this thesis, the value of the soil survey beyond agricultural applications is demonstrated. Engineers already use the soil survey to determine site suitability. Other disciplines could utilize the information available in the survey. A few examples include geologists, hydrologists, and ecologists.

It is also important to recognize the soil survey's current limitations. Incongruities between county maps need to be resolved to enable better regional studies. Because GIS can manage more soil attributes, information useful to many disciplines can be readily displayed in a map and spatially analyzed. The current national soil survey geospatial data does not show signs of implementing nationally consistent attribute tables. Increased dialog between all disciplines that could benefit from spatial soil information could resolve mapping incongruities and provide useful information for more fields of study at little additional cost.

APPENDIX A. PARENT MATERIAL & LANDSCAPE POSITION CODES

Zonal Code			Position Code	Parent Material Description	Land Position Code
UF	**Unformed**		0	General	UF0
			1	Urban	UF1
			3	Ents	UF3
			5	Eroded	
			6	Unformed Deposition	UF6
			7	Unformed Sand	
			8	Lagoon	UF8
			9	Water	UF9
HO	**Holocene**		0	River Valley Bottom	HO0
			10	General Floodplain	HO10
			11	Floodplain, low stream terraces, drainageways	HO11
			12	General Stream Terrace, recent	HO12
			13	Alluvial fans, upland toeslopes, stream terraces	HO13
			14	Alluvium associated w/ glacial fluvial	HO14
			15	Floodplain, Slackwater/Backwater	HO15
			16	Floodplain, fine over sand	HO16
			17	Stream Terrace of outwash	HO17
			18	Stream Terrace	HO18
			19	Floodplain, footslopes derived from upslope materials	HO19
			21	Side Slope Alluvium	HO21
			22	Side Slope Colluvium	HO22
			23	Glacial Till reworked by wind	HO23
			24	Local Eolian	HO24
			26	Beach	HO26
			28	Escarpment	HO28
		Wetlands	30	Marsh (Wet & Organic)	HO30
			35	Sphagnum wetland	HO35
		Terraces	40	General Holocene Terrace	HO40
			45	Terrace Escarpment	
		Industrial	80	General Man-made/Industrial	HO80
			81	Man-built structure	HO81
			82	Man-made pit	HO82
			83	Cuts & Fills	HO82
			85	Reconstructed Mining Area	HO85
			91	Erosional, Gullies	HO91

Zonal Code		Position Code	Parent Material Description	Land Position Code
WG	**Wisconsinan Glacial**			
	Till	7	Till shallow to bedrock	WG7
		10	General Ground Moraine	WG10
	Till-derived alluvium	11	Upland Depression	WG11
	Till-derived alluvium	12	Depression Rim	WG12
	Till-derived alluvium	13	Upland Swale, WT influenced	WG13
	Till-derived alluvium	14	Upland Swale, moderate WT influence	WG14
		15	Upland Flat, WT influenced	WG15
		16	Upland Flat, w/o WT influence	WG16
		17	Convex sideslopes	WG17
		18	Upland extra hummocky (undulating)	WG18
		19	Upland Convex	WG19
	Glacial Lacustrine	20	Lacustrine Plain	WG20
		21	Lacustrine Depressional	WG21
		22	Lacustrine calcareous	WG22
		23	Lacustrine Swale	WG23
		24	Lacustrine Plain, possibly ice walled	WG24
		25	Lacustrine, modern bog	WG25
		26	Lacustrine associated with river valley	WG26
		27	Lacustrine w/ Outwash	WG27
		28	Lacustrine with loess mantle	WG28
		29	Lacustrine Convex	WG29
	Glacial Depositional	30	General	WG30
		31	Esker	WG31
		32	Kame terrace	WG32
		33	Kame hill	WG33
		34	Kame plateau	WG34
		35	Moulin kame	WG35
		36	Kame delta	WG36
	Glacial Erosional	40	General	WG40
		41	Tunnel Channel	WG41
		42	Tunnel Valley	WG42
		43	Spillway	WG43
		45	Drumlin	WG45
		48	Till, steep slope	WG48

Zonal Code		Position Code	Parent Material Description	Land Position Code
WG	**Wisconsinan Glacial**			
	Morainal	50	General	WG50
		51	Moraine Concave	WG51
		52	Moraine Flat	WG52
		53	Moraine Footslope	WG53
		55	Morainal concave to convex, drumlins?	WG55
		57	Moraine Outwash	WG57
		59	Moraine Convex	WG59
	Glacial Fluvial	60	Outwash Plain	WG60
		61	Outwash Depression	WG61
		62	Glaciofluvial Alluvium	WG62
		63	Swale in Outwash	WG63
		64	Outwash w/ Alluvium Cover	WG64
		65	Outwash/Stream Terrace (Valley Train?)	WG65
		66	Outwash mantle on till	WG66
		67	Outwash w/ maybe Eolian	WG67
		68	Outwash Sandy	WG68
		69	Outwash Convex	WG69
		70	Dissected	WG70
		72	Side-slope	WG72
		81	Transitional Alluvium	WG81
		82	Transitional Colluvium	WG82
		83	Wind & water laid loamy deposits	WG83
		85	Upland Floodplains	WG85
		88	Loamy Sediments associated w/ glaciolacustrine	WG88
		89	Till derived floodplain	WG89
WL	**Wisconsinan Loess**			
		4	Sandy Eolian	WL4
	On Till Uplands	10	General Ground Moraine covered by Loess	WL10
		11	Loess Depressional	WL11
		13	Swale	WL13
		17	Till Plain	WL17
		19	Loess on convex till	WL19
	On Erosional Structures	40	General	WL40
		41	Loess on Stream Terrace Depression	WL41
		42	Loess on old Stream Terrace	WL42
		45	Stream Terrace w/ underlying limestone	WL45

Zonal Code		Position Code	Parent Material Description	Land Position Code
WL	**Wisconsinan Loess**			
	On Depositional Structures	50	General	WL50
		59	Loess on Moraine	WL59
	On Glacial Outwash	60	Loess on Outwash Plain	WL60
		61	Loess on Outwash Depression	WL61
		62	Loess on Glaciofluvial Alluvium	WL62
		63	Loess on Swale	WL63
		64	Loess on Outwash w/ Alluvium Cover	WL64
		65	Loess on Outwash/Stream Terrace (Valley Train?)	WL65
		66	Loess on Outwash mantle on till	WL66
		67	Loess on Outwash w/ maybe Eolian	WL67
		68	Loess on Outwash Sandy	WL68
		69	Loess on Outwash Convex	WL69
	On Dissected Till	70	Till plain hills	WL70
		71	Footslope	WL71
		72	Side-Slope	WL72
		73	East-facing Side-slope	WL73
		74	West-facing Side-slope	WL74
		75	Upland Drainageways	WL75
		76	Undulating (concave through convex)	WL76
		77	Summit-Shoulder	WL77
		78	Summit-Flat	WL78
		79	Summit-Convex	WL79
	Loess Transitional	80	General	WL80
		81	Transitional Alluvium	WL81
		82	Transitional Colluvium	WL82
		85	Loess on structural benches	WL85
		88	Loamy sediments from glaciolacustrine	WL88
		91	Interfluves/Side-slopes underlain by Y-S paleosol	WL91

Zonal Code		Position Code	Parent Material Description	Land Position Code
PIG	**Pre-Illinoisan Glacial**			
	Till	10	Unknown	PIG10
		11	Upland Depression	PIG11
		12	Depression Rim	PIG12
		13	Upland Swale, WT influenced	PIG13
		14	Upland Swale, moderate WT influence	PIG14
		15	Upland Flat, WT influenced	PIG15
		16	Upland Flat, w/o WT influence	PIG16
		17	Till shallow to bedrock	PIG17
		18	Upland Flat	PIG18
		19	Upland Convex	PIG19
	Glacial Lacustrine	20	Lacustrine Plain	PIG20
		21	Lacustrine Depressional	PIG21
		22	Lacustrine associated with river valley	PIG22
		24	Lacustrine Plain, possibly ice walled	PIG24
		25	Lacustrine, modern bog	PIG25
		28	Lacustrine with loess mantle	PIG28
		29	Lacustrine Convex	PIG29
	Glacial Depositional	30	General	PIG30
		31	Esker	PIG31
		32	Kame terrace	PIG32
		33	Kame hill	PIG33
		34	Kame plateau	PIG34
		35	Moulin kame	PIG35
		36	Kame delta	PIG36
	Glacial Erosional	40	General	PIG40
		41	Tunnel Channel	PIG41
		42	Tunnel Valley	PIG42
		43	Spillway	PIG43
		45	Drumlin	PIG45
		48	Till, steep slope	PIG48
	Morainal	50	General	PIG50
		51	Moraine Concave	PIG51
		52	Moraine Flat	PIG52
		53	Moraine Convex	PIG53
		55	Morainal concave to convex, drumlins?	PIG55

Zonal Code		Position Code	Parent Material Description	Land Position Code
PIG	**Pre-Illinoisan Glacial**			
	Glacial Fluvial	60	Outwash Plain	PIG60
		61	Outwash Depression, silty	PIG61
		62	Outwash Depression, sandy	PIG62
		63	Outwash Depression, S&G	PIG63
		64	Outwash Depression, Organic	PIG64
		65	Valley Train	PIG65
		66	Outwash mantle on till	PIG66
		67	Outwash w/ maybe Eolian	PIG67
		68	Outwash Sandy	PIG68
		69	Outwash Convex	PIG69
	Dissected Till	70	General	PIG70
		71	Footslope	PIG71
		72	Side-Slope	PIG72
		73	Side-slope Paleosol	PIG73
		75	Flat Upland Drainageways	PIG74
		76	Summit-Shoulder	PIG75
		77	Summit-Convex	PIG76
		78	Summit-Flat	PIG77
	Transitional	80	General	PIG80
		81	Transitional Alluvium	PIG81
		82	Transitional Colluvium	PIG82
		85	Till on treads & risers of structural benches	PIG85
		91	Interfluves/Side-slopes underlain by Y-S paleosol	PIG91
IE	**Iowa Erosional**	0	General	IE0
		6	Loamy Sediments on Bedrock, Interfluves & Side Slopes	IE6
		10	Unknown	IE10
		11	Upland Depression	IE11
		13	Swale	IE13
		18	Upland Flat	IE18
		19	Upland Convex	IE19
		60	Loamy Sediment on Outwash Plain	IE60
		66	Loamy Sediment on Outwash over Pre-Illinoisan till	IE66
		71	Loamy Sediment	IE71
		73	Loamy Sediments on Till, Convex, low-relief, side slopes	IE73
		76	Loamy Sediments on Till, Interfluves & Side Slopes	IE76

Zonal Code		Position Code	Parent Material Description	Land Position Code
IE	Iowa Erosional			
		85	Loamy Sediments on treads & risers of structural benches	IE85
		91	Interfluves/Side-slopes underlain by Paleosol	IE91
		95	Loamy Sediments with stone line	IE95
BR	Bedrock	0	Unknown, General Outcrop	BR0
		1	Till Mantle over unknown bedrock	BR1
		5	Steep rock	BR5
		9	Combo Residuum (Sandstone, Limestone, Shale)	BR9
		10	Limestone	BR10
		11	Limestone w/ thin mantle of till	BR11
		12	Limestone w/ alluvium mantle	BR12
		14	Limestone w/ Loess cover	BR14
		15	Limestone w/ Loamy Sediments cover	BR15
		16	Limestone on High Benches	BR16
		20	Shale	BR20
		24	Shale w/ Loess cover	BR24
		25	Shale Residuum	BR25
		30	Gabbro/Granite	BR30
		31	Gabbro/Granite w/ thin mantle of till	BR31
		32	Granitic Gneiss	BR32
		40	Sandstone	BR40
		42	Sandstone derived solum, broad upland summit	BR42
		45	Sandstone w/ Loamy Sediment Cover	BR45
		47	Eolian from sandstone	BR47
		60	Sioux Quartzite	BR60
		64	Sioux Quartzite w/ Loess cover	BR64
		65	Sioux Quartzite w/ Loamy Sediments	BR65

APPENDIX B. SOILS IDENTIFIED AS POSSIBLE DEPRESSIONS

All soil delineations were visually checked for accuracy. Extra scrutiny was applied to those map units whose description warranted the possibility of being a depression, but could also include non-depressional areas. The possible depression soils were categorized as: clear depression, mixed complex, all depression complex, floodplain depression, potential depression, or ponded water. A mixed complex is a map unit that has both depressional and non-depressional soils within that are not separately delineated. Possible depression soils that were a mixed complex or a floodplain depression were not included.

Clear Depressions – Soils whose description clearly identified a depression.

Name	Surface Parent Material	Map Unit Kind
Adolph	Dows Till	Consociation
Adolph Muck	Dows Till	Consociation
Adrian	Organic	Consociation
Adrian Muck	Organic	Consociation
Arveson	Glacial Lacustrine	Consociation
Augsburg	Glacial Lacustrine	Undifferentiated group
Baden Muck	Glacial Lacustrine	Consociation
Berner Muck	Organic	Consociation
Bigstone	Dows Till Alluvium	Consociation
Biscay	Glacial Outwash	Consociation
Blackhoof Muck	Organic	Consociation
Blue Earth	Glacial Lacustrine	Consociation
Blue Earth Muck	Glacial Lacustrine	Consociation
Bluffton	Superior Till Alluvium	Consociation
Boots Muck	Organic	Consociation
Borup Muck	Glacial Lacustrine	Consociation
Brophy Peat	Organic	Consociation
Calcousta	Glacial Lacustrine	Consociation
Calcousta Muck	Glacial Lacustrine	Consociation
Carlos Muck	Organic	Consociation
Caron Muck	Organic	Consociation
Cathro Muck	Organic	Consociation
Clearwater Muck	Glacial Lacustrine	Consociation
Cormant	Glacial Lacustrine	Consociation
Dassel	Glacial Outwash	Consociation
Deerwood Muck	Organic	Consociation
Deford	Glacial Outwash	Complex
Dimmick	Glacial Lacustrine	Consociation
Dora Muck	Organic	Consociation
Dovray	Glacial Lacustrine	Consociation
Edina	Peoria Loess	Consociation
Eramosh Peat	Glacial Lacustrine	Consociation
Giese	Superior Till	Consociation
Gilford	IL Loess	Consociation
Glencoe	Dows Till Alluvium	Consociation
Greenwood	Organic	Undifferentiated group

Clear Depressions (continued)

Name	Surface Parent Material	Map Unit Kind
Greenwood Mucky Peat	Organic	Consociation
Greenwood Peat	Organic	Consociation
Grygla	Glacial Lacustrine	Consociation
Hamre Muck	Organic	Consociation
Harps	Dows Till	Consociation
Harps	Dows Till	Consociation
Harpster	Glacial Lacustrine	Consociation
Haslie Muck	Organic	Consociation
Heil	Dows Till Alluvium	Consociation
Histosols	Organic	Consociation
Histosols-Fens	Organic	Consociation
Histosols-Haplaquolls	Organic	Undifferentiated group
Houghton	Glacial Lacustrine	Consociation
Houghton Muck	Glacial Lacustrine	Consociation
Houghton-Muskego	Glacial Lacustrine	Undifferentiated group
Klossner	Organic	Undifferentiated group
Klossner Muck	Organic	Consociation
Knoke	Glacial Lacustrine	Consociation
Knoke Muck	Glacial Lacustrine	Consociation
Kratka	Glacial Lacustrine	Consociation
Lanyon	Glacial Lacustrine	Consociation
Leafriver Muck	Organic	Consociation
Lena Muck	Organic	Consociation
Lindaas	Glacial Lacustrine	Consociation
Loamy Wetland	Dows Till	Consociation
Lobo Peat	Sphagnum Organic	Consociation
Lundlake	Wadena Till Colluvium	Consociation
Lupton Muck	Organic	Consociation
Lupton Muck Peat	Organic	Consociation
Lura	Glacial Lacustrine	Consociation
Markey Muck	Glacial Outwash	Consociation
Marsh	Organic	Consociation
Martisco	Organic	Consociation
Medo	Organic	Undifferentiated group
Medo Muck	Organic	Consociation
Merwin Muck	Organic	Consociation
Merwin Peat	Organic	Consociation
Millerville Mucky Peat	Organic	Consociation
Muck	Organic	Consociation
Muck-Calcareous	Organic	Consociation
Muck-Peat-Calcareous	Organic	Consociation
Muskego	Organic	Consociation
Muskego Muck	Organic	Consociation
Nidaros Muck	Organic	Consociation
Northwood Muck	Glacial Lacustrine	Consociation
Okoboji	Dows Till Alluvium	Consociation

Clear Depressions (continued)

Name	Surface Parent Material	Map Unit Kind
Okoboji Muck	Dows Till Alluvium	Consociation
Oldham	Dows Till Alluvium	Consociation
Palms	Organic	Consociation
Palms Muck	Organic	Consociation
Parnell	Dows Till	Consociation
Peotone	Trafalgar Till Colluvium	Consociation
Percy	Glacial Lacustrine	Undifferentiated group
Perella	Glacial Lacustrine	Consociation
Perella-Colvin	Glacial Lacustrine	Complex
Prebish	Dows Till	Consociation
Quam	Glacial Lacustrine	Consociation
Quam Muck	Glacial Lacustrine	Consociation
Rifle	Organic	Undifferentiated group
Rifle Muck	Organic	Consociation
Rifle Muck Peat	Organic	Consociation
Rifle Peat	Organic	Consociation
Rockwell	Glacial Lacustrine	Consociation
Rolfe	Dows Till Alluvium	Consociation
Roliss	Glacial Lacustrine	Consociation
Romnell	Dows Till	Consociation
Roscommon Muck	Glacial Outwash	Consociation
Rosedell	Glacial Lacustrine	Consociation
Runeberg	Wadena Till	Consociation
Runeberg Mucky	Wadena Till	Consociation
Sago Mucky Peat	Organic	Consociation
Seelyeville Muck	Organic	Consociation
Seelyeville Mucky Peat	Organic	Consociation
Selma	Glacial Outwash	Consociation
Southam	Dows Till Alluvium	Consociation
Spicer	Glacial Lacustrine	Consociation
Spicer-Quam	Glacial Lacustrine	Complex
Tacoosh Muck	Organic	Consociation
Tacoosh Mucky Peat	Organic	Consociation
Talmoon Muck	Glacial Lacustrine	Consociation
Tetonka	Dows Till Alluvium	Consociation
Tonka	Dows Till Alluvium	Consociation
Urness	Glacial Lacustrine	Consociation
Urness Mucky	Glacial Lacustrine	Consociation
Verendrye	Glacial Outwash	Consociation
Wacousta	Glacial Lacustrine	Consociation
Warman	Glacial Outwash	Consociation
Will	Glacial Outwash	Consociation

Mixed Complex – Soils whose description indicated the inclusion of both depressional and non-depressional soils. These were typically found in the drier areas of northern Minnesota and North Dakota. Not included for delineation of wetlands.

Name	Surface Parent Material	Map Unit Kind
Aastad-Tonka	Dows Till	Complex
Aastad-Wynard-Tonka	Dows Till	Complex
Arveson-Hamar	Glacial Lacustrine	Undifferentiated group
Badger-Tonka	Dows Till Alluvium	Complex
Balkan-Balkan	Unassociated Till	Complex
Baltic	Alluvium	Consociation
Barronett-Barronett	Glacial Lacustrine	Complex
Bearden-Quam	Glacial Lacustrine	Complex
Bearden-Tetonka	Glacial Lacustrine	Complex
Bearden-Tonka	Glacial Lacustrine	Complex
Bergland-Cuttre	Glacial Lacustrine	Complex
Berner-Markey	Organic	Complex
Berner-Rosewood-Strathcona	Organic	Undifferentiated group
Bigstone-Parnell	Dows Till Alluvium	Undifferentiated group
Blackhoof-Cathro-Baden	Organic	Complex
Blackhoof-Mahtow	Organic	Undifferentiated group
Blomford-Northwood	Glacial Outwash	Complex
Borup-Colvin-Perella	Glacial Lacustrine	Undifferentiated group
Bowbells-Tonka	Dows Till	Complex
Brownton-Lura	Glacial Lacustrine	Complex
Canisteo	Dows Till Alluvium	Consociation
Canisteo-Glencoe	Dows Till Alluvium	Complex
Cathro-Barber	Organic	Complex
Cathro-Hassman	Organic	Undifferentiated group
Cathro-Seelyeville-Grasston Catena	Organic	Undifferentiated group
Colvin-Oldham	Glacial Lacustrine	Complex
Colvin-Perella	Glacial Lacustrine	Undifferentiated group
Comfrey	Glacial Outwash	Consociation
Cordova-Rolfe	Dows Till Alluvium	Complex
Corvuso-Lura	Glacial Lacustrine	Complex
Crowriver-Lundlake	Wadena Till	Complex
Cubden-Tonka	Dows Till	Complex
Deford-Leafriver	Glacial Outwash	Complex
Duluth-Culver-Cathro	Organic	Complex
Duluth-Sanburn-Cathro	Organic	Complex
Effie-Hamre	Organic	Complex
Egglake-Cathro	Wadena Till	Complex
Enet-Storla-Tetonka	Alluvium	Complex
Fargo	Glacial Lacustrine	Consociation
Fenander	Glacial Lacustrine	Consociation
Fieldon-Dassel	Glacial Outwash	Complex
Flom	Dows Till	Consociation
Flom-Vallers	Dows Till	Undifferentiated group
Forada	Glacial Outwash	Undifferentiated group

Mixed Complex (continued)

Name	Surface Parent Material	Map Unit Kind
Forestcity-Lundlake	Wadena Till Colluvium	Complex
Friberg	Wadena Till Colluvium	Consociation
Gilby-Tonka	Glacial Lacustrine	Complex
Greatscott-Nashwauk-Balkan	Dows Till	Complex
Greenwood-Duluth	Organic	Consociation
Greenwood-Greatscott	Organic	Undifferentiated group
Greenwood-Hibbing	Organic	Undifferentiated group
Greenwood-Taylor	Organic	Undifferentiated group
Greenwood-Upham	Organic	Undifferentiated group
Hamel-Glencoe	Dows Till Colluvium	Complex
Hamerly-Aazdahl-Lindaas	Dows Till	Complex
Hamerly-Barnes-Tonka	Dows Till	Complex
Hamerly-Lindaas	Dows Till	Complex
Hamerly-Tonka	Dows Till Alluvium	Complex
Hamerly-Tonka-Parnell	Dows Till Alluvium	Complex
Hamlet-Hamerly-Tonka	Dows Till Alluvium	Complex
Hamlet-Tonka	Dows Till Alluvium	Complex
Hanska	Glacial Outwash	Consociation
Harps-Glencoe-Seaforth	Dows Till	Complex
Harps-Seaforth-Okoboji	Dows Till	Complex
Hedman	Unassociated Till	Consociation
Hermantown-Canosia-Giese	Superior Till	Complex
Hulligan	Superior/Rainy Outwash	Consociation
Indus-Dora	Glacial Lacustrine	Complex
Indus-Woodslake	Glacial Lacustrine	Complex
Isan	Glacial Outwash	Consociation
Isanti	Glacial Outwash	Consociation
Kandota-Egglake	Wadena Till	Complex
Kapla-Wabuse	Glacial Lacustrine	Complex
Kato	Peoria Loess	Consociation
Kerkhoven-Friberg	Wadena Till	Complex
Klossner-Harps-Mayer	Organic	Complex
Kranzburg-Cresbard-Tonka	Dows Till	Complex
Kratka-Strathcona	Glacial Lacustrine	Undifferentiated group
Lakepark-Parnell	Dows Till	Complex
Leen-Okoboji	Dows Till Alluvium	Complex
Lemond	Glacial Outwash	Consociation
Marna-Barbert	Glacial Lacustrine	Complex
Marshan	Glacial Outwash	Consociation
Marysland	Glacial Outwash	Consociation
Mayer	Glacial Outwash	Consociation
Mayer-Biscay	Glacial Outwash	Complex
Mazaska-Rolfe	Dows Till Alluvium	Complex
McQuade-Daisybay-Fayal	Peoria Loess	Complex
McQuade-Fayal	Peoria Loess	Complex
Merwin Peat-Duluth Catena	Organic	Consociation
Merwin Peat-Greatscott Catena	Organic	Consociation

Mixed Complex (continued)

Name	Surface Parent Material	Map Unit Kind
Normanna-Giese	Dows Till	Complex
Northwood-Berner	Organic	Complex
Okoboji-Canisteo	Dows Till Alluvium	Complex
Oldham-Parnell	Dows Till Alluvium	Undifferentiated group
Parnell	Dows Till	Consociation
Parnell-Lallie	Dows Till	Undifferentiated group
Parnell-Tonka	Dows Till	Undifferentiated group
Parnell-Vallers	Dows Till	Complex
Peever-Tonka	Dows Till	Complex
Perella-Bearden	Glacial Lacustrine	Complex
Prophetstown	Loess	Consociation
Rifle-Duluth Catena	Organic	Consociation
Rifle-Greatscott Catena	Organic	Undifferentiated group
Rifle-Hibbing Catena	Organic	Undifferentiated group
Rifle-Tacoosh	Organic	Complex
Rifle-Taylor Catena	Organic	Undifferentiated group
Rifle-Upham	Organic	Undifferentiated group
Rockwell-Kratka	Glacial Lacustrine	Undifferentiated group
Smiley Muck	Organic	Consociation
Spicer-Lura	Glacial Lacustrine	Complex
Spooner-Sax	Glacial Lacustrine	Complex
Strathcona-Kratka	Glacial Lacustrine	Undifferentiated group
Svea-Hamerly-Tonka	Dows Till Alluvium	Complex
Svea-Tonka	Dows Till Alluvium	Complex
Tacoosh Mucky Peat-Duluth Catena	Organic	Consociation
Tacoosh Mucky Peat-Greatscott Catena	Organic	Consociation
Tadkee-Tadkee	Glacial Lacustrine	Complex
Tetonka-Canisteo	Dows Till Alluvium	Complex
Tetonka-Chancellor	Dows Till Alluvium	Complex
Tetonka-Davison-Clanro	Dows Till Alluvium	Complex
Tetonka-Parnell	Dows Till Alluvium	Undifferentiated group
Tetonka-Stickney	Dows Till Alluvium	Complex
Tonka-Hamerly	Dows Till Alluvium	Complex
Tonka-Parnell	Dows Till Alluvium	Undifferentiated group
Vallers-Tonka	Dows Till	Complex
Williams-Bowbells-Tonka	Dows Till	Complex
Williams-Cresbard-Tonka	Dows Till	Complex
Winger-Balaton-Parnell	Glacial Lacustrine	Complex

All Depression Complex - Soils whose description indicated the inclusion of multiple soils that were all depressional. These usually described a single depressional wetland with variances in characteristics such as depth or duration of ponding.

Name	Surface Parent Material	Map Unit Kind
Arveson-Cormant	Glacial Lacustrine	Undifferentiated group
Augsburg-Wabanica	Glacial Lacustrine	Undifferentiated group
Calcousta-Okoboji	Glacial Lacustrine	Complex
Caron-Blue Earth-Palms	Organic	Undifferentiated group
Cathro-Sago	Organic	Complex
Cathro-Seeyleville	Organic	Undifferentiated group
Cathro-Twig	Organic	Undifferentiated group
Cathro-Twig-Adolph	Organic	Undifferentiated group
Cathro-Twig-Giese	Organic	Undifferentiated group
Glencoe-Dassel	Dows Till Alluvium	Complex
Greenwood-Lobo	Organic	Complex
Greenwood-Merwin	Organic	Complex
Harps-Glencoe	Dows Till	Complex
Harps-Okoboji	Dows Till	Complex
Haslie-Nidaros	Organic	Undifferentiated group
Haslie-Seelyeville-Cathro	Organic	Undifferentiated group
Heil-Mckenzie	Dows Till Alluvium	Consociation
Klossner-Lundlake	Organic	Undifferentiated group
Klossner-Muskego	Organic	Undifferentiated group
Klossner-Okoboji	Organic	Complex
Klossner-Okoboji-Glencoe	Organic	Complex
Leafriver-Deford-Markey	Glacial Outwash / Organic	Complex
Medo-Dassel-Biscay	Organic	Undifferentiated group
Muskego-Blue Earth-Houghton	Organic	Undifferentiated group
Muskego-Houghton Muck	Organic	Undifferentiated group
Muskego-Klossner	Organic	Undifferentiated group
Muskego-Peotone	Organic	Undifferentiated group
Okoboji-Harps	Dows Till Alluvium	Complex
Okoboji-Palms	Dows Till Alluvium	Undifferentiated group
Palms-Glencoe	Organic	Complex
Palms-Okoboji	Organic	Undifferentiated group
Prebish-Histosols	Dows Till	Undifferentiated group
Quam-Cathro-Urness	Glacial Lacustrine	Undifferentiated group
Rockwell-Grygla	Glacial Lacustrine	Undifferentiated group
Seelyeville-Bowstring	Organic	Undifferentiated group
Seelyeville-Cathro	Organic	Undifferentiated group
Seelyeville-Markey	Organic	Complex
Tacoosh Mucky Peat-Upham	Organic	Consociation
Talmoon-Hamre	Glacial Lacustrine	Complex
Tetonka-Hoven	Dows Till Alluvium	Complex
Tonka-Nishon	Dows Till Alluvium	Complex
Tonka-Rimlap	Dows Till Alluvium	Complex
Twig-Tachoosh-Giese	Superior Till	Complex

Floodplain Depression - Soils whose description indicated a depression in the floodplain. Because this study was only interested in upland depressions, this category was not used.

Name	Surface Parent Material	Map Unit Kind
Albaton	Alluvium	Consociation
Ludden	Alluvium	Consociation
Luton	Alluvium	Consociation
Moundprairie	Alluvium	Consociation
Newalbin	Alluvium	Consociation
Newalbin-Palms	Alluvium	Complex
Shandep	Glacial Outwash	Consociation
Wann	Alluvium	Consociation
Zook	Alluvium	Consociation

Ponded Water – Map units that were not described as soils because of standing water. Delineations from this category could be anything from existing depressional wetlands to impoundments. This category was included, but heavily scrutinized with an aerial photo and elevation hillshade.

Name	Surface Parent Material	Map Unit Kind
Aquolls-Histosols	Organic	Undifferentiated group
Aquolls-Marsh	Water	Consociation
Int. Water	Water	Consociation
Intermittent	Water	Consociation
Lakes	Water	Consociation
Misc Water	Water	Consociation
Water	Water	Consociation

Potential Depressions – Soils whose description indicated the potential to be a depression, but also could describe a non-depressional area. This category was included, but heavily scrutinized with an aerial photo and elevation hillshade.

Name	Surface Parent Material	Map Unit Kind
Aquents	Water	Consociation
Aquents-Histosols	Organic	Undifferentiated group
Aquents-Udorthents	Water	Complex
Aquents-Urban	Water	Complex
Aquepts	Water	Consociation
Aquolls	Water	Consociation
Aquolls-Aquents	Water	Undifferentiated group
Barbert	Glacial Lacustrine	Consociation
Borosaprists	Organic	Consociation
Borup	Glacial Lacustrine	Consociation
Dassel Muck	Glacial Outwash	Consociation
Drummer	IL Loess	Consociation
Drummer-Barrington-Mundelein	IL Loess	Complex
Drummer-Milford	IL Loess	Complex
Drummer-Urban	IL Loess	Complex
Dunham	IL Loess	Consociation
Epoufette Muck	Glacial Outwash	Consociation
Forada	Glacial Outwash	Consociation
Giese	Superior Till	Consociation
Hamar	Sand	Consociation
Hassman Muck	Glacial Lacustrine	Consociation
Lobo-Washkish	Sphagnum Organic	Complex
Lobo-Waskish Peats	Sphagnum Organic	Undifferentiated group
Mayer	Glacial Outwash	Consociation
Milford	Glacial Lacustrine	Consociation
Northcote	Glacial Lacustrine	Consociation
Sago-Roscommon	Organic	Undifferentiated group
Salt Water Marsh	Water	Consociation
Selma	Glacial Outwash	Consociation
Sperry	Peoria Loess	Consociation
Tiffany	Glacial Outwash	Consociation
Urban-Drummer-Barrington	IL Loess	Complex

GENERAL REFERENCES

Batt, D.J., M.G. Anderson, C.D. Anderson, and F.D. Caswell. 1989. The Use of Prairie Potholes by North American Ducks. p. 204-267. In *Northern Prairie Wetlands*. ed. A.G. van der Valk. Ames, Iowa: Iowa State University Press.

Beauchamp, K.H. 1987. A History of Drainage and Drainage Methods. p. 13-29. In: *Farm Drainage in the United States: History, Status, and Prospects*. United States Department of Agriculture, Economic Research Service. Miscellaneous Publication Number 1455.

Galatowitsch, S.M. and A.G. van der Valk. Restoring Prairie Wetlands: An Ecological Approach. Ames, Iowa: Iowa State University Press, 1994.

Gosselink, J.G. and E. Maltby. 1990. Wetland Losses and Gains. p. 29-322. In: M. Williams, ed. *Wetlands: A Threatened Landscape*. Oxford, England: B. Blackwell Ltd.

Jenny, Hans. Factors of Soil Formation: A System of Quantitative Pedology. New York, New York: McGraw-Hill, 1941.

Khan, F.A. and T.E. Fenton. 1994. Saturated zones and soil morphology in a mollisol catena of central Iowa. *Soil Science Society of America Journal*. 58:1457-1464.

Lindholm, R.C. 1994. Information Derived from Soil Maps: Areal Distribution of Bedrock Landslide Distribution and Slope Steepness. Environmental Geology. v.23, p. 271-275.

Shjeflo, J.B.1968. Evapotranspiration and the water budget of prairie potholes in North Dakota. *U.S. Geological Survey Professional Paper 585-B*. Washington D.C.: U.S. Government Printing Office.

Sloan, C.E. 1972. Ground-Water Hydrology of Prairie Potholes in North Dakota. *U.S. Geological Survey Professional Paper 585-C*. Washington D.C.: U.S. Government Printing Office.

Soil Survey Staff. 2003. *Keys to Soil Taxonomy, Ninth Edition*. Unites States Department of Agriculture, Natural Resources Conservation Service.

van der Valk, A.G. and C.B. Davis. 1978. The Role of Seed Banks in the Vegetation Dynamics of Prairie Glacial Marshes. *Ecology*. Vol.59, No.2, p.322-335.

Vepraskas, M.J. 1994. Redoximorphic features for identifying aquic conditions. North Carolina Agric. Res. Serv. Technical Bulletin 301. North Carolina State University, Raleigh, North Carolina.

Vepraskas, M.J. and S.P. Faulkner. 2001. Redox chemistry of hydric soils. p. 85-105. *In* J.L. Richardson and M.J. Vepraskas (ed.) Wetland soils: Their genesis, hydrology, landscape and separation into hydric and nonhydric soils. CRC Press, Boca Raton, FL.

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